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The duration of response inhibition in the stop-signal paradigm varies with response force

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Abstract

In a previous study, we have found that the speed of stopping a response is delayed when response readiness is reduced by cuing the probability of no-go trials [Acta Psychol. 111 (2002) 155]. Other investigators observed that responses are more forceful when the probability to respond is low than when it is high (e.g. [Quart. J. Exp. Psychol. A 50 (1997) 405]). In this study, the hypothesis was tested that low probability responses are more forceful than high probability responses and that these responses are more difficult to stop. Subjects performed on a choice reaction task and on three tasks with respectively 100%, 80%, and 50% response probabilities. Stop signals were presented on 30% of the trials, instructing subjects to withhold their response. Response force on non-signal (go) trials and the duration of response inhibition on signal (stop) trials increased as response probability decreased. This pattern of findings was interpreted to support the hypothesis predicting that stopping is more difficult when response readiness is low than when it is high.

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1. Introduction

The ability to stop motor responses is an important act of control that can be investigated in a laboratory setting using the stop-signal paradigm (Logan, 1994; Logan & Cowan, 1984). In the stop-signal paradigm, the subject is usually engaged in a primary choice reaction time (RT) task requiring the subject to press one of two keys with the index fingers as quickly as possible after the presentation of the reaction stimulus. In addition to this primary task, the subject has to stop the prepared or ongoing response when an occasional stop signal is presented. The chances of successful stopping depend on the timing of the stop signal relative to the primary-task signal. Response inhibition is easy when the stop signal is presented shortly after the primary-task signal but becomes increasingly difficult, or virtually impossible, when stop-signal delay is increased and approaches the moment of response execution (e.g. Lappin & Eriksen, 1966; Logan, 1994; Logan & Cowan, 1984).

Performance on the stop task has been conceptualized as the outcome of a race between two sets of processes—going and stopping (Lappin & Eriksen, 1966; Logan & Cowan, 1984; Vince, 1948). The response will be executed if the go process wins the race, whereas the response will be withheld if the stop process wins the race. Given the assumption of independence between stopping processes and go processes, it is possible to calculate the time required for stopping the response; that is, the stop-signal reaction time (SSRT). It appears that the horse-race model describes empirical data quite well (for a review see Logan, 1994) and simulation studies have demonstrated that estimates of SSRT are fairly reliable (Band, van der Molen, & Logan, 2003).

The stop-signal paradigm has been applied successfully to examine inhibitory control under a variety of experimental conditions. For example, the SSRT of young adults is close to 200 ms when they try to interrupt continuous actions such as typing (Logan, 1982), over-learned responses such as speaking (Ladefoged, Silverstein, & Papcun, 1973), or incompatible responses (Logan, 1981). The stop-signal paradigm has not only been used in human subjects but also in monkeys (Hanes, Patterson, & Schall, 1998). Stopping has been examined in children (Band, van der Molen, Overtoom, & Verbaten, 2000; Ridderinkhof, Band, & Logan, 1999; Schachar & Logan, 1990) and in the elderly (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; for life-span studies see Bedard et al., 2002; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). The stop-signal paradigm has indicated deficiencies in inhibitory control in clinical groups, including ADHD children (Jennings, van der Molen, Pelham, Brock, & Hoza, 1997; Oosterlaan & Sergeant, 1998; Overtoom et al., 2002; Schachar & Logan, 1990). In other studies, effects of methylphenidate (Tannock, Schachar, Carr, Chajczyk, & Logan, 1989) and alcohol (Mulvihill, Skilling, & Vogel-Sprott, 1997) have been studied. Finally, investigators used the stop-signal paradigm to assess inhibitory control as reflected by single-cell brain activity (Hanes et al., 1998), brain potentials (De Jong, Coles, & Logan, 1995; De Jong, Coles, Logan, & Gratton, 1990; Van Boxtel, van der Molen, Jennings, & Brunia, 2001), heart rate changes (Jennings, van der Molen, Brock, & Somsen, 1992) or muscle activation (McGarry & Franks, 1997).

Although the race model fits most data fairly well, the model does not address the nature of the stopping process as such (cf. Logan, 1994). One way to achieve a better understanding of the nature of stop-signal inhibition is provided by studies that combine stopping and other forms of inhibition. Two recent studies employed stop signals in an Eriksen flanker task and found that responses to target stimuli that were flanked by incompatible distracters were more difficult to inhibit than responses to compatible displays (Kramer et al., 1994; Ridderinkhof et al., 1999). On the basis of these results, it was suggested that stopping and the requirement to suppress responding to incompatible flankers, queue up or compete for execution due to restrictions in mental capacity (cf. Ridderinkhof et al., 1999).

In a previous study, we adopted a similar strategy by crossing stop-signal inhibition and the probability of responding (Van den Wildenberg, van der Molen, & Logan, 2002). Subjects performed a primary task requiring a speeded binary choice reaction on go trials and response inhibition on no-go trials. An occasional cue informed subjects that a no-go trial was imminent but left them uncertain about the number of go trials separating the cue and the upcoming no-go trial. This setup was meant to induce tonic inhibition (i.e., episodes of reduced response readiness). The tonic inhibition episodes were contrasted with control episodes during which subjects were ready to execute a speeded choice reaction (i.e., trial sequences consisting of go trials only). During both episodes, a visual stop signal could occasionally and unpredictably follow the go-signal onset, instructing subjects to withhold their response to the go signal. Responding on go trials was delayed during tonic inhibition episodes relative to control episodes suggesting that cuing reduced the readiness to respond. Most importantly, stopping was delayed during tonic inhibition episodes. This pattern of findings was interpreted with reference to a response readiness model suggested by Mattes, Ulrich, and Miller (1997); see also Ulrich, Mattes, and Miller (1999).

Mattes et al. (1997) induced reduced response readiness by increasing the relative frequency of no-go signals in go/no-go tasks. They observed that more forceful responses were produced when the probability of a go signal was low than when it was high. Likewise, Ulrich et al. (1999) have found that responses on go trials in a go/no-go task were more forceful than responses on simple and choice RT tasks (see also Jaśkowski & Wlodarczyk, 1997). Mattes and co-workers proposed an extended version of Näätänen's (1971) response readiness model (see also Niemi & Näätänen, 1981) to explain their findings. According to this model, subjects establish a criterion, known as the motor-action limit, and trigger an overt response when response readiness reaches this criterion. Subjects adjust their response readiness close to the motor-action limit only when they expect the respond signal to arrive because it is assumed that maintaining a high level of response readiness is difficult and an energy consuming process. The *variable-increment* version of this model, proposed by Mattes and co-workers, assumes that detection of the respond signal causes an increment to the motor activation level that depends on the distance needed to reach the motor-action limit. Given the noise inherent in the motor system, it is further assumed that the system generates a pulse of activation that is somewhat larger (i.e., overshoot) than the minimum necessary to cross the motor-action limit. The probability findings observed by Mattes et al. (1997) were then explained by assuming that the motor system produces a larger overshoot (i.e., more forceful responses) when subjects are unprepared (low go-signal probability) than when they are prepared (high go-signal probability). Along similar lines, we posited the hypothesis that responses executed during episodes of tonic inhibition (i.e., periods of reduced response readiness) are stopped less easily and that these responses are associated with more force output than responses executed during control episodes (i.e., periods of high preparation) (Van den Wildenberg et al., 2002). The prediction of longer stopping latencies for responses that are generated with increased response force is in accord with the overshoot model. The experiment reported in the current study was designed to test this hypothesis.

The experimental design comprised four tasks, the standard choice reaction task, which is commonly used as a primary task in the stop-signal paradigm, and three tasks with varying response probabilities. On all tasks, subjects were asked to respond to left- or right-pointing arrows. In the choice reaction task, a left-pointing arrow required a left-hand response and a right-pointing arrow required a right-hand response. In the other three tasks, subjects responded to the arrows with a right-hand response. In one task, the probability of responding was 100% (i.e., a simple or Donders a-task) and in the other two tasks, the probability of responding was either 80% or 50% (go/no-go or Donders c-tasks). In the stop tasks, a stop signal was presented randomly at 30% of the trials instructing subjects to withhold the planned response. Response force measures were taken in all tasks in addition to measures of response speed and accuracy. Based on previous studies, it was predicted that (a) SSRTs would be longer for choice compared to simple reactions (Logan, Cowan, & Davis, 1984), (b) response force would not differentiate between choice and simple reactions, as the probability to respond was 100% in both tasks (see Ulrich et al., 1999), and that (c) response speed would decrease but response force would increase when response probability is lowered (Mattes et al., 1997). Most importantly, it was predicted that SSRT would be longer when the probability of responding is low than when it is high and that low probability responses are more forceful than high probability responses.

2. Method

2.1. Subjects

Twenty-three undergraduate students (13 females and 10 males, $M = 21.9$ years of age, $\mathrm{SD} = 3$ years) participated to fulfill course requirements. They were all right-handed and had normal or corrected-to-normal vision. Each subject participated in a single session of approximately three hours.

2.2. Apparatus and signals

The subjects were seated in a comfortable reclining chair with supports for hands, arms, and legs. Stimuli were presented against the black background of a 14-in. monitor that was placed 1 m in front of the subject at eye level. The imperative signals were green left- and right-pointing arrows, subtending a visual angle of 1.72°. Signal duration was 1500 ms and the time interval between the onsets of subsequent trials varied between 1250 and 1750 ms in steps of 125 ms. During the interval, a white fixation square was presented that subtended a 0.4° visual angle. All stimuli were horizontally and vertically centered on the midpoint of the computer screen.

Subjects responded by means of a single press with the left- or right-index finger on one of two zero-displacement force transducers (Kyowa LM-20KA) integrated within hand supports. Each transducer generated a proportional voltage that was A/D converted and analyzed online. The sampling rate of the force transducer was 200 Hz with a 12-bit resolution, thus a timing resolution of 5 ms. The amplitude resolution was 1.22 mV. Baselines were computed over 500 ms prior to the respond signal. Response onset was defined at 2% of the maximum voluntary force (MVF) and response completion was set at 15% of the maximum force.

2.3. Tasks and design

The experimental design comprised four reaction tasks: a standard choice reaction task and three tasks with varying response probabilities; a simple reaction task with 100% response probability and two go/no-go tasks with 80% and 50% response probabilities. In the simple and the choice task, 50% of the arrows pointed to the left, and 50% pointed to the right. In the choice reaction task, subjects responded to a left-pointing arrow with their left hand and to a right-pointing arrow with their right hand. In the simple reaction task, subjects responded with their right hand to all arrows. In the go/no-go tasks subjects responded only with their right hand to right-pointing arrows (i.e., go signals) whereas subjects had to refrain from responding to left-pointing arrows (i.e., no-go signal). Presentation order was randomized within blocks.

The four tasks were presented in two formats. In the *standard paradigm,* the tasks were presented in their typical format. In the *stop-signal paradigm*, an occasional stop signal was introduced to the tasks. The stop signal, presented on 30% of the trials, consisted of a color change of the arrow—from green to red. The timing of the color change was dynamically adjusted and targeted at 50% correct inhibits using a tracking algorithm (Levitt, 1971). Upon successful stopping, the stop-signal delay on the next stop trial was increased by 50 ms. Failures to inhibit were followed by a 50 ms decrease in stop-signal delay.

2.4. Procedure

For each subject, individual MVF was measured for each index finger before administration of the experimental tasks. We asked the subject to press the force transducer as hard as they possibly could for about 5 s while care was taken that only the index finger was involved in the pressure built-up. After alternating between index fingers about five times, we selected the highest peak-force value for each index finger as an indication of MVF. Stop trials were classified as *signal-respond* trials if the force exceeded 15% of the MVF. If the force remained below a criterion of 15%, the trial was classified as a *signal-inhibit* trial. Subjects were instructed to respond as quickly and accurately as possible to green go-arrows and to avoid errors of commission to no-go arrows pointing to the left in the go/no-go tasks. With respect to the stopping tasks, subjects were told that the color of the green arrow would occasionally change to red, requiring them to refrain from pressing the response button. It was explained that stop-signal delay varied across trials so that on some trials stopping would be easy whereas on other trials stopping would be difficult.

In the standard paradigm, the simple and choice RT task consisted of 120 trials each. In the standard paradigm, the 80% and 50% go/no-go tasks consisted of 125 and 200 trials, respectively. In the stop paradigm, the simple and choice RT task both contained 180 trials. In the stop paradigm, the 50% go task was administered in two blocks of 180 trials each and the 80% go task contained one block of 225 trials. Task order was counterbalanced across participants. Half of the subjects started each task with the standard paradigm, the other half started with the stop paradigm. Each task was practiced for at least 100 trials in a separate practice block. There were short intermissions between test blocks and a 15-min break halfway the test session.

2.5. Response force recordings

Several dependent measures were calculated for each response force function (see also Mattes et al., 1997; Ulrich et al., 1999). The first set of force measures included (i) peak force, or the maximum force value attained in that trial, (ii) time to peak force, the interval from onset until the maximum of the output as an indication of the latency of the force output, and (iii) the impulse size, the total force integrated over time in a single trial. The second set of measures described the shape of the force–time functions and included (i) dispersion, or the duration of force output, (ii) skewness, a measure of the degree of asymmetry of the force function, and (iii) kurtosis as an indication of its peakedness (Ulrich, Wing, & Rinkenauer, 1995).

2.6. Data reduction and analysis

The first four trials of each block of trials were viewed as warm-up trials and were discarded from further analysis. Individual mean RTs of correct trials were calculated after the removal of outliers from the RT distribution (i.e., RTs $> M \pm 2.5$ SD) on a subject-by-subject basis.

SSRT was estimated using the horse-race model (Logan & Cowan, 1984). Following the horse-race model's independence assumption, the RT distribution of the go process is the same whether or not a stop signal is presented. This implies that the left side of the distribution of RTs on non-signal trials, representing fast RTs, matches the distribution of RTs on stop trials that escape inhibition. The latency of the stop process can be estimated from the start and the finish of the stop process. The start of the stop process is under experimental control by the stop-signal delay, but the finish time has to be inferred from the observed non-signal RT distribution. If responses are not stopped on n% of the stop trials, the finish of the stop process should be equal to the *n*th percentile of the RT distribution on non-signal RTs. Finally, mean stop-signal delay is subtracted from this finish time to obtain an estimate of stop latency (for a detailed exposition see Logan, 1994).

3. Results

3.1. Reaction times

3.1.1. Go-signal reaction times

Table 1 shows the mean values for each dependent RT measure. An overall MANOVA on RTs was conducted with within-subject factors of Task (simple, choice, 50% go, and 80% go) and Paradigm (standard paradigm vs. stop-signal paradigm). The main effect of Task was highly significant, $F(3,20) = 69.7$, $p < 0.001$. Pairwise comparisons confirmed that all RT differences between tasks were highly significant (*p*s < 0.01). Simple RTs were shortest, followed by RTs in the go/no-go task with 80% go signals, and 50% go signals, respectively. Responses in the binary choice task were slowest.

Responses on standard task trials (i.e., without stop signals) were faster than responses on non-signal trials in the stop-signal task (264 vs. 295 ms, respectively), $F(1,22) = 43.45$, $p < 0.001$. Some tasks were more prone to this slowing than others, as indicated by a significant interaction between Task and Paradigm, $F(3,20) = 13.90$, $p < 0.001$. Post-hoc comparisons showed that the slowing of responses was more pronounced in the simple and 80% go/no-go tasks compared to the choice and 50% go/no-go tasks ($p < 0.001$).

Right-hand responses in the simple task were 4 ms faster on average when the arrow pointed to the right (i.e., compatible with respect to the response hand) than when it pointed to the left, $F(1,22) = 7.50$, $p = 0.01$. [1] This effect did not interact with Paradigm ($F < 1$). Choice responses with the right hand were 10 ms faster on average than responses with the left hand, $F(1,22) = 15.51$, $p < 0.001$. This RT difference between hands did not differ between standard and stop-signal paradigm ($F = 1$).

There were less than 5% errors of omission. More choice errors were committed with the right hand (3%) than with the left hand (2%), $F(1,22) = 10.41$, $p = 0.004$, and more premature responses were recorded for the right hand (6%) than for left-hand responses (1%), $F(1,22) = 58.97$, $p < 0.001$. None of the error measures mentioned above interacted significantly with Paradigm (*p*s > 0.09).

As can be seen in Table 1, increasing the probability of no-go trials led to an increased RT to go signals; RTs were longer in the 50% go/no-go task than in the 80%

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[1] A 4 ms advantage for spatially compatible responses in the simple RT task has been reported previously (Poffenberger, 1912; Ulrich et al., 1999). This has been attributed to neuronal transfer times of information between stimulated and response generating hemispheres. However, the RT bias observed in the current experiment cannot be readily interpreted in terms of hemispheric transfer times because the imperative signals of the present experiment were presented in the center of the screen.

Table 1
Mean reaction times and standard deviations per task and paradigm

RT measure	Task							
	Choice		Simple		80% go		50% go	
	M	SD	*M*	SD	*M*	SD	*M*	SD
Standard paradigm								
Reaction time	309	33	194	23	262	30	290	33
Stop-signal paradigm								
Non-signal RT	326	41	252	44	292	45	309	41
Stop-signal RT	191	40	149	29	150	36	174	34
Stop-signal delay	124	68	93	58	130	67	129	57
Response ratio (%)	46.1	4.3	48.6	5.3	47.7	4.1	48.3	3.5

go/no-go task, $F(1,22) = 24.70$, $p < 0.001$. The RT difference between probabilities was somewhat larger in the standard paradigm (28 ms) than in the stop paradigm (17 ms), as indicated by a significant interaction between Task (50% vs. 80% go/no-go) and Paradigm (standard vs. stop signal), $F(1,22) = 4.88$, $p < 0.05$. The likelihood of committing a false alarm was considerably higher in the 80% go/no-go task compared to the 50% go/no-go task (17% vs. 3%, respectively), $F(1,22) = 83.98$, $p < 0.001$. In sum, decreasing the likelihood that a go response will be required increased RT on go trials and decreased the proportion of false alarms on no-go trials. This pattern is suggestive of a decrease in response readiness when response probability is lowered.

3.1.2. Stop-signal reaction times

The stopping results are presented in Table 1. SSRTs were estimated for each subject and for each task separately. First of all, subjects were able to stop their responses on stop-signal trials successfully in about half of the times a stop signal instructed them to do so. The tracking algorithm resulted in an overall percentage of 48% correct inhibits which is close to the anticipated 50%. The tracking algorithm worked very well for all tasks as the proportion of correct inhibits did not differ significantly between stop tasks, $F(3,20) = 1.60$, $p = 0.22$. Stop-signal delay varied significantly across stop tasks, $F(3,20) = 4.90$, $p = 0.01$, with follow-up analyses indicating that stop-signal delay was shortest in the stop task with simple responses (93 ms) compared to the delays in the other stop tasks, $F(1,22) = 14.60$, $p = 0.001$.

As predicted by the horse-race model, responses on stop trials that escaped inhibition were significantly faster than responses on non-signal trials, $F(1,22) = 71.85$, $p < 0.001$. The differences in RT between failed inhibits and responses on non-signal trials were strikingly similar across stop tasks, about 125 ms ($F < 1$).

An overall analysis of mean SSRTs yielded a significant main effect of Task, $F(3,20) = 17.33$, $p < 0.001$. Post-hoc comparisons, adjusted for multiple comparisons using Bonferoni correction, revealed that SSRTs in the choice task were slowest compared to the other tasks, $F(1,22) = 37.88$, $p < 0.001$. Go responses in the go/no-go task with 80% go-signal probability were stopped more quickly than responses in the go/no-go task with 50% go-signal probability ($p = 0.02$). Finally, stop-signal RTs derived from the simple task did not differ significantly from stop-signal RTs in the 80% go condition ($F < 1$).

3.2. Force measures

A summary of the force measures is presented in Table 2. Response force functions obtained for the standard tasks are presented in Fig. 1. The first set of analyses compared the force output in the choice task with the force characteristics of responses in the simple RT task. According to expectation, none of the dependent force measures distinguished between the simple and the choice reaction tasks: mean peak force of the response, $F < 1$, integrated force, $F < 1$, time to peak force, $F(1,22) = 2.33$, $p = 0.14$, dispersion values, $F < 1$, skewness, $F(1,22) = 1.47$, $p = 0.24$, and kurtosis, $F < 1$.

Secondly, planned contrast analyses on mean peak force values demonstrated that responses in the 50% go/no-go task were more forceful than in the simple and choice RT tasks, $F(1,22) = 5.60, p = 0.01$. In addition, the total amount of integrated force over time was larger in the 50% go/no-go task than in the choice and simple RT tasks, $F(1,22) = 3.86, p = 0.06$. Peak timing was significantly shorter in the go/no-go task, $F(1,22) = 4.10, p = 0.05$. Analysis of dispersion indicated that the duration of force output was longer in the 50% go/no-go task compared to the simple and choice tasks, $F(1,22) = 5.71, p = 0.03$. Skewness and kurtosis did not differ significantly between tasks (p-values of 0.20 and 0.53, respectively).

A final set of ANOVA analyses performed on response force measures obtained in the simple task (i.e., 100% go responses) and the go/no-go tasks (i.e., 80% and 50%

Table 2
Mean dependent force measures and standard deviations by task and paradigm

Force measure	Task							
	Choice		Simple		80% go		50% go	
	M	SD	*M*	SD	*M*	SD	*M*	SD
Standard paradigm								
Peak force (% mvf)	43.0	19.9	43.3	18.4	44.5	20.6	48.6	23.7
Time to peak force	130.7	44.9	121.4	41.0	118.7	36.7	114.6	30.6
Integrated force	23.9	10.5	24.0	10.0	24.6	11.6	26.5	13.0
Dispersion	14.2	7.1	14.3	6.5	14.8	7.4	16.3	8.5
Skewness	−0.14	0.13	−0.11	0.16	−0.10	0.14	−0.09	0.15
Kurtosis	−1.43	0.07	−1.43	0.10	−1.46	0.09	−1.45	0.09
Stop-signal paradigm								
Peak force (% mvf)	44.3	20.7	41.8	22.3	46.1	21	48.3	23.6
Time to peak force	123.7	39.4	121.0	39.1	122.4	33.9	116.8	28.8
Integrated force	24.8	11.4	23.3	12.3	25.4	11.8	26.3	12.7
Dispersion	14.7	7.4	13.8	8.0	15.4	7.6	16.1	8.4
Skewness	−0.14	0.14	−0.13	0.15	−0.09	0.14	−0.09	0.15
Kurtosis	−1.43	0.06	−1.44	0.08	−1.46	0.07	−1.44	0.09

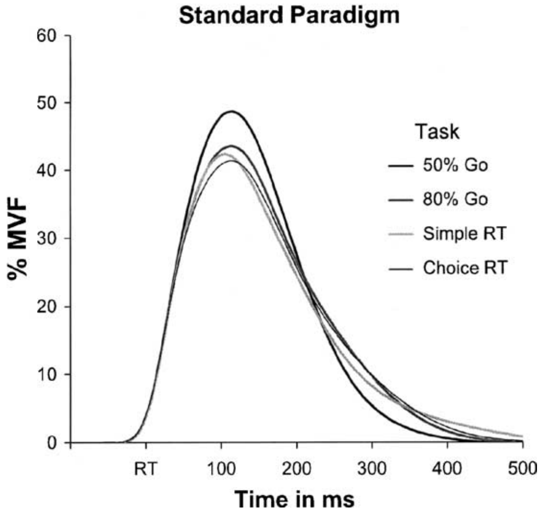

Fig. 1. Grand averages of response force waveforms represented as percentage of the maximum voluntary force (MVF) computed over subjects and per condition for the standard paradigm tasks. Note that the waveforms are synchronized with respect to the reaction time (RT-locked) that was defined at 2% of the MVF. For average values of maximum force output the reader is referred to the peak-locked averages presented in Table 2.

go responses) showed a reliable main effect of relative go-signal probability on response force, $F(2,44) = 3.31$, $p < 0.05$ (with p values using the Greenhouse–Geisser correction for violations of the sphericity assumption). Response force increased in a linear fashion, $F(1,22) = 6.44$, $p = 0.02$, when the relative frequency of go signals decreased from 100% to 80% and 50% (peak forces are 42.6%, 45.3%, and 48.5% MVF, respectively). Follow-up analysis indicated that responses in the simple task were less forceful compared to go responses in the 50% go/no-go task ($p < 0.01$). The difference in peak force values between the 80% go/no-go task and the simple task did not approach significance ($p = 0.12$). The difference in response force between the 80% go/no-go task and the 50% go/no-go task just failed to reach significance ($p = 0.09$). The other force measures did not distinguish either between the 80% and 50% go/no-go tasks (ps > 0.10). Finally, none of the force output measures differentiated between standard tasks and stop-signal tasks (ps > 0.10).

4. Discussion

The present study set out to examine the hypothesis that the duration of the stop process varies with response force when response probability differs between tasks. The pattern of findings was straightforward. Response force increased when response probability decreased and the duration of the stop process varied with response force. Considering first the relation between response probability and response force, the current findings provide almost an exact replication of the results reported previously by Ulrich et al. (1999) and Mattes et al. (1997). As in the Ulrich et al. report (experiment 1), the current findings showed shorter simple RTs than choice RTs but no differences between force output measures associated with simple and choice reactions. In addition, as in the Ulrich et al. report (experiment 3), the current findings showed that subjects produced significantly more forceful responses in the go/no-go task than in the choice task. Finally, as in the Mattes et al. study (experiment 1), the current findings showed that subjects produced more forceful responses when the probability of responding decreased from 100%, through 80% to 50%. Moreover, the current force patterns did not differ between the standard and stop-signal tasks substantiating the robustness of the relation between response probability and response force.

The comparable levels of peak force exerted on the choice and simple RT tasks might be taken to suggest that the level of response readiness is comparable between the two tasks. According to the "overshoot model" the distance between the internal levels of response readiness and the action threshold is comparable, and so is the amount of overshoot when a response is called for. The conjecture of similar levels of response readiness for choice and simple responses seems plausible because an overt motor response is called for on 100% of the trials on the choice RT task as well as on the simple RT task. For this reason it seems to be a beneficial strategy for subjects to maintain a high level of response readiness in the choice RT task.

In this respect it is relevant to point to an apparent discrepancy between the observation of 17% no-go false alarms in the 80% go/no-go task, whereas in the choice task, presumed to be related to relatively higher levels of response readiness, only 2–3% choice errors were committed. It should be noted that such a comparison requires a more detailed analysis of partial (incorrect) response trials in the choice task. On these trials, the correct response was executed but the other (incorrect) response was activated with force levels between 2% and 15% MVF. The proportions of partial response trials were 13.0% and 14.1% for the standard and stop-signal tasks, respectively. Thus, the proportions of partial responses and erroneous responses sum to about 16%, a proportion that comes close to the proportion of commission errors in the go/no-go task.

Mattes et al. (1997) interpreted the relation between response probability and response force within the context of the variable increment version of Näätänen's motor readiness model. According to the original model, the latency of responding will depend on the distance between the level of response readiness and the motor-action limit. When the subject is highly prepared, response readiness will be close to the motor-action limit so that only a small increment is needed to cross the limit. Alternatively, when the subject is in a relatively unprepared state a larger increase in response readiness is needed to cross the limit. The variable increment version of this model proposed by Mattes et al. (1997) assumes that the motor system must produce a greater amount of activation when the subject is unprepared, thereby producing a greater overshoot. It is further assumed that the amount of force output increases with the degree of activation overshoot. The model thus predicts slower but forceful responses when subjects are relatively unprepared compared to when subjects are in a highly prepared state. The current results are in perfect agreement showing that response speed decreases and response force increases when the probability of responding is lowered. This interpretation of the relation between response force and response probability in terms of preparatory processes of the motor system might be incomplete. A recent study by Mattes, Ulrich, and Miller (2002) on response force in RT tasks suggests that next to response probability, stimulus probability affects the forcefulness of the response. They argued that response probability exerts a direct influence on the motor system, whereas stimulus probability influences the motor system indirectly via premotoric adjustments.

Turning now to the data from the stop-signal tasks, it should be noted first that the insertion of stop-signals delayed responding on trials when no stop signal was presented (i.e., non-signal trials). This is a typical result in the stop-signal task literature, and is usually interpreted to suggest that subjects delay their responses to increase the probability of response inhibition (e.g., Logan, 1994). Obviously, this strategy is pointless when a tracking algorithm for determining stop-signal delays is used, which is targeted at a particular probability of successful inhibits (in this study set at 50%). The delay in responding when stop signals were introduced to the tasks was somewhat more pronounced for the simple and 80% go/no-go tasks compared to the 50% go/no-go and choice tasks. This finding is consistent with the literature showing that mixing costs are usually larger in easy conditions compared to more difficult conditions (for a review see Los, 1999). SSRTs varied across tasks. Consistent with previous reports (e.g., Logan et al., 1984), SSRTs were longer when a choice reaction had to be stopped compared to the stopping of a simple reaction. It might be argued that the requirement to suppress responding with the wrong hand in the choice task in favor of the correct response hand might compete with the stopping instruction. The small percentage of choice errors in the choice task (2–3%) indicated that participants were quite successful in suppressing the response activation of the incorrect hand. A similar interpretation in terms of competition between two manifestations of inhibition has been formulated by Ridderinkhof et al. (1999) to explain slower stopping of responses to incongruent stimulus arrays in the Flanker task.

Most importantly, SSRT increased when the probability of responding decreased from 100% to 50%. In addition, as in the standard tasks, the force of responding on non-signal trials increased when response probability was lowered. The increase in SSRT associated with a decrease in response probability is consistent with our previous finding showing that SSRT is prolonged when the subject is in a relatively unprepared state (Van den Wildenberg et al., 2002). The current findings provide support for the hypothesis suggested to account for this relation. In line with the variable increment model proposed by Mattes et al. (1997), the hypothesis assumes that more forceful responses are executed when the subject is relatively unprepared that are then more difficult to inhibit. The current findings are consistent with this prediction in that they show that a decrease in response probability is associated with more forceful responses and longer SSRTs.

Franz and Miller (2002) related the differences in response force between participants diagnosed with Parkinson's disease and normal controls to later stages of information processing that appear to be mediated by the basal ganglia as a likely candidate for involvement in response activation. A model of impaired basal ganglia function (i.e., Parkinson's disease) was linked to the inability to adjust the internal level of response readiness and the subsequent relatively forceful responses on high-frequent trials and a general problem of inhibiting motor output when responses are to be withheld.

Before closing, two additional points need to be made. One refers to the apparent discrepancy between the effects of response probability and the insertion of stop signals to the task. The decrease in response probability was associated with slower but more forceful responses. The introduction of stop signals to the tasks delayed responding on non-signal trials but this delay was not associated with an appreciable change in response force. Most likely, this discrepancy is more apparent than real. Consider for example the simple task. Decreasing the probability of responding to 50% resulted in an approximate 100 ms increase in the delay of responding on go trials. This delay was associated with a significant increase in the force of responding. Decreasing the probability of responding to 80% increased the delay of responding with about 70 ms, but response force failed to discriminate between the simple and 80% go/no-go task. Introducing stop signals to the simple task delayed the speed of responding on non-signal trials by about 60 ms, but failed to produce a significant effect on response force. This pattern seems to suggest that introducing stop signals to the tasks may have lowered the subject's readiness to respond, but not to an extent manifested in the force of overt responding on go or non-signal trials.

The other point refers to the most important finding of the current study; i.e., the observation that the duration of stopping is longer for more forceful responses. It could be argued that this relation presents a challenge to the independence assumption of the horse-race model. The model assumes stochastic independence between stopping and go processes, meaning that their durations are not correlated. Violations of stochastic independence are thought to compromise estimates of SSRT (e.g., Logan, 1994; Logan & Cowan, 1984). Simulation studies indicated, however, that estimates of SSRT based on tracking 50% successful inhibits are fairly robust against violations of the independence assumption of the horse-race model (Band et al., 2003; De Jong et al., 1990).

In conclusion, the present results demonstrate a relation between the speed of response inhibition and the subject's readiness to respond. This finding may have important implications for factorial studies examining the nature of stopping. For example, stop signals have been presented in Eriksen flanker tasks (Kramer et al., 1994; Ridderinkhof et al., 1999) to assess whether the alleged inhibition of responses to incongruent flankers or of inappropriate responses to the source of stimulation would interact with the inhibition of the correct response required by the stop signal. The typical finding is that SSRT is longer for responses on incongruent or non-corresponding trials. These and similar findings are typically interpreted to imply that stopping and the need to inhibit the (incorrect) response to incompatible flankers or to the source of stimulation queue up or compete for execution (for a review see Van den Wildenberg et al., 2002). The current findings suggest that an interpretation of these findings in terms of response force may provide a viable alternative or at least that potential differences in response force should be considered when interpreting interactions between stopping and other varieties of response inhibition.

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