

Countermanding saccades: Evidence against independent processing of go and stop signals

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In a stop signal paradigm, subjects were instructed to make a saccade to a visual target appearing left or right of the fixation point. In 25% of the trials, an auditory stop signal was presented after a variable delay that required the subject to inhibit the saccade. Observed saccadic response times in stop failure trials were longer than predicted by Logan and Cowan's (1984) race model. Saccadic response time and amplitude decreased with the time between stop signal presentation and saccade execution, suggesting an inhibitory effect between the stop signal and the go signal processes that is not compatible with an independent race assumption. Moreover, countermanding a saccade was more difficult when stop and go signals appeared at the same location.

The stop signal paradigm is a valuable tool for the investigation of inhibitory control of voluntary action. Inhibitory performance is assessed by randomly intermixing two kinds of trials within one experimental block. The primary task for the subject is to respond to the target as quickly as possible (*go task*). The secondary task requires the subject to withhold the response whenever an infrequently presented stop signal occurs with one out of several possible delays after target presentation (*stop task*). Probability of successful inhibition in the stop task critically depends on the time delay between the go and the stop signals (*stop signal delay*, SSD). Stop signal behavior has been studied with simple manual responses (Lappin & Eriksen, 1966; Logan, 1981; Logan & Cowan, 1984; Ollman, 1973), hand squeezes (De Jong, Coles, Logan, & Gratton, 1990), and arm movements (Henry & Harrison, 1961; Kudo & Ohtsuki, 1998; see Logan, 1994, for a review). In a series of recent studies, the stop signal paradigm has also been applied to investigations of the control of oculomotor behavior in both humans and the macaque (Hanes, Patterson, & Schall, 1998; Hanes & Schall, 1995, 1996; Logan & Irwin, 2000; Stuphorn, Taylor, & Schall, 2000). The primary task in these experiments is a saccadic response toward a visual target; the secondary task is to suppress a saccade. Usually, the stop signal presented in the saccadic countermanding task is a visual signal—for example, the reappearance of the fixation point—but auditory and combined visual–auditory stop signals have also been utilized (Cabel, Armstrong, Reingold, & Munoz, 2000; Colonus, Özyurt, & Arndt, 2001).

Behavior in the stop signal task has been interpreted in terms of statistically independent go and stop signals rac-

ing toward their thresholds (Hanes & Carpenter, 1999). This race model (Logan & Cowan, 1984) allows estimation of the average time for the stop signal to reach its threshold, the stop signal processing time (SSPT). Depending on experimental conditions, estimates for SSPT range from 50 to 150 msec—that is, the time it takes to cancel a movement seems to be shorter than the time it takes to prepare a saccade.

In general, the race model has been very successful in accounting for the data in stop signal studies. However, at short SSDs, several data sets contain stop failure response times (RTs) that are larger than those predicted by the race model (Hanes & Carpenter, 1999; Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984). This tendency does not usually reach statistical significance, since only a few responses (stop failures) occur for brief SSDs. However, the consistent occurrence of this finding in different studies and under different experimental conditions is noteworthy and hints at possible violations of the independence assumption, at least at small SSDs. In our recent countermanding study (Colonus et al., 2001), we used very small SSDs for a subject (M.R.) with very short latencies to achieve a stopping performance comparable to that of the other subjects. Interestingly, Subject M.R. showed strong violations of the model in terms of prolonged RTs, again most pronounced for short SSDs. These results led us to suspect that the independence assumption may be violated at short SSDs more generally, possibly owing to inhibitory processes evoked by the stop signal. Obviously, an inhibitory influence of the stop signal on the go signal process would not be reconcilable with the independence assumption of the race model (cf. Asrress & Carpenter, 2001).

The aim of this study was to investigate this hypothesis more systematically. Therefore, we developed an experimental paradigm permitting the collection of a sufficient number of observations at short SSDs. The critical

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factor in this paradigm is the control for possible subject strategies. In countermanding experiments, subjects commonly have considerable leeway in carrying out the stopping task. It is well known that subjects try to delay their response to the go signal when they are confronted with a countermanding task—that is, latencies are longer than in simple RT tasks (Lappin & Eriksen, 1966; Ollman, 1973). This procrastination strategy depends on experimental conditions, such as frequency of the stop signal, the employed delays between go and stop signals, and so forth. (Logan, 1994). Obviously, the results of countermanding tasks are affected by this strategy. Among other effects, it results in a low rate of (erroneous) stop signal responses for small SSDs.

EXPERIMENT

In this experiment, subjects were first trained on the eye movement task without any stop signals occurring (visual task). This gave us a measure of the subjects' individual speed levels that was not affected by any possible strategies elicited by the stop signal task. In the subsequent stop signal task, the subjects were given feedback whenever their response speed in go trials fell below the level they had achieved in the preceding visual task. This allowed us to check whether or not they were employing a delay strategy. Moreover, if they did follow the speed instruction in accordance with the feedback they received, we would expect a sufficient number of responses (i.e., stop failures) even for rather short SSDs. These responses then would permit a valid test of our hypothesis of an inhibitory influence of the stop signal on the go signal processing.

Using both a visual go and a visual stop signal may lead to some interference very early in the visual pathway. In order to preclude this somewhat less interesting version of our hypothesis of interaction between the signals, in the experiment reported here an auditory noise signal was used as a stop signal for inhibiting a saccadic response toward a visual target stimulus. Auditory stop signals have proved to be effective in the countermanding of saccades in previous studies (Cabel et al., 2000; Colonius et al., 2001). In particular, since the auditory stop signal was presented off the fixation point, we expected, in accordance with a hypothesis of Schall and Thompson (1999; see below), that this manipulation would lead to a relatively high rate of stop failures even for short SSDs.

Both the stop and the go signals were presented randomly either left or right of the fixation point in order to test for possible position effects. On the basis of the different functional roles of central and peripheral regions in both the frontal eye fields and the superior colliculus, it has been suggested by Schall and Thompson (1999) that the effectiveness of a visual stop signal presented foveally may be due to its direct activation of the gaze fixation system. Evidence against this hypothesis comes from a recent study by Asrress and Carpenter (2001), which

showed no significant differences between central and peripheral visual stop signals. Colonius et al. (2001) did not find any effect of the spatial position of the auditory stop signal on countermanding performance. However, in that study, the position of the stop signal was completely random (left or right), so that subjects could not anticipate the direction of the stop signal. Therefore, in this experiment, stop signal position was held constant over the block of trials so that the subjects would know where the stop signal would occur, if it occurred at all. If a position effect were to be found, it could point to two different mechanisms. First, there could be a general spatial attention shift, in the sense that subjects will monitor more closely the side of the expected stop signal. Second, there could be a specific spatial effect, in the sense that an auditory stop signal is simply more effective when it is close to (alternatively, more distant from) the go signal, in analogy to the distinction between foveal and peripheral positions in the purely visual setup. Note that under the first hypothesis, a difference between the expected and the nonexpected sides should show up in the responses to the go signal even if the stop signal does not occur.

Method

Subjects

Three subjects (M.R., male, age 42; D.L., female, 23; P.T., male, 28) with normal hearing abilities and normal or corrected-to-normal visual acuity were tested. All the subjects had right-eye dominance. The experiment was carried out with the understanding and consent of each subject.

Apparatus and Stimuli

The subjects were seated in a darkened, sound-attenuated chamber (1.0 × 1.2 × 1.9 m). The head was held steady by a dental impression plate. Visual stimuli were presented on a 37-in. monitor (XP37, NEC) at a distance of 57 cm. Monitor update rate was 75 Hz. Auditory stimuli (noise signal with a bandwidth of 500–14000 Hz) were presented via a virtual acoustic environment through headphones (Sennheiser HD 580). The noise signal was convolved with head-related transfer functions of a dummy head to generate the three auditory positions used in the experiment. The subjects were presented with an intensity of 72 dB SPL. The rise time of the noise signal was 5 msec. White dots with a diameter of 0.1° served as visual targets and fixation point (19.8 cd/m²) and were presented on a dark background (less than 0.01 cd/m²). The presentation of both stimuli was controlled by a PC; a second PC was employed for data acquisition. The temporal arrangements of stimulus presentation and data acquisition were synchronized with the exact presentation time of the visual stimulus determined by the monitor update rate.

Response Recording and Detection

Eye movements were measured with an infrared light reflecting system (IRIS, Skalar Medicals) in both training and experimental sessions. This system provides an analog signal of the eye position that was digitized at a rate of 1 kHz and stored for further analysis. Spatial resolution after calibration and digitalization was maximally 0.2°. Saccade onsets and offsets were identified automatically, using velocity criteria (50°/sec for onsets and 20°/sec for offsets). The accuracy of the computer-generated marks was verified by inspection of the records displayed on a graphics monitor. Trials that included blinks, small saccades or drifts larger than 0.8° during fixation, anticipations (latencies less than 80 msec), or other errors

were excluded from further analysis. Saccades larger than 1° in the direction of the target that were carried out during the first 500 msec after target presentation were considered to be responses. Saccadic RT was determined as the time difference between target onset and saccade onset. For the analysis of saccadic amplitudes, only data from measurements with good and stable calibration were used.

Pretest: Visual Task

Prior to the countermanding task, we conducted a pretest to assess the subjects' mean RTs to visual targets when no stop signal was to be expected. Visual stimuli were presented randomly on the horizontal plane either 15° to the right or 15° to the left of fixation. The subjects were told to maintain stable fixation until the visual stimulus was presented and then to perform a speeded saccadic response toward the visual target. Each subject attended two sessions, with 160 training and 240 experimental trials altogether. After having run the subsequent countermanding experiment, they were requested to perform the visual task again for one session of 40 training and 160 experimental trials. No feedback was given in the visual task.

Countermanding Task

Design. Both visual go stimuli and auditory stop signals were presented on the horizontal plane at two different positions (left, -15°; right, +15°). Within one experimental block, visual stimuli were randomly presented either to the left or to the right of the fixation point, whereas auditory stimuli were presented at only one of the two possible positions. An experimental block with an auditory signal presented at a given position (e.g., right) was always followed by a block with an auditory stimulus presented at the other position (e.g., left). Three (for Subjects M.R. and P.T.) or four (for Subject D.L.) different SSDs were applied with equal probabilities (individual time delays for stop signals are shown for each subject in Table 2). A combination of 2 visual stimuli × 2 auditory stimuli × 3 (or 4) SSDs resulted in 12 (or 16) stop conditions. Stop trials were randomly interspersed with control trials, each experimental block consisting of 72 (or 96) trials altogether. Each subject performed 40 experimental blocks presented over 8–10 sessions.

Experimental procedure. Each trial started with the onset of the central fixation point and lasted for 1,300–4,000 msec until fixation point offset. Trial duration was dependent on the variable fixation period (800–3,500 msec), which was followed by the presentation of the visual go signal for 500 msec. In 25% of the experimental trials, an auditory stop signal was presented for 500 msec after one of the possible stop signal delays. Intertrial time was 1.5 sec, starting 2 sec after the onset of the visual target. At the end of each experimental block, the subjects received feedback about their mean RTs and the proportions of successfully inhibited reactions in stop signal trials. The subjects were instructed to fixate properly and to make a saccade in the direction of the visual stimulus as quickly as possible. They were instructed to inhibit their reaction toward the target if an auditory signal was presented. Moreover, they were told that they were not allowed to delay their response to the go signal in favor of a better stopping performance. They were informed about their mean RTs, determined in a previous session run without stop signals (visual task), and they were asked to maintain the same speed level.

Training procedure for the countermanding task. The subjects took part in four (M.R.), nine (D.L.), and eight (P.T.) training sessions within the countermanding paradigm. The training served to speed up their performance, in order to get RTs comparable to those in the visual task and to determine individual SSDs for the countermanding experiment. The individual delays were set to obtain probabilities of inhibition of approximately .7, .5, and .3.

Distribution Inequality Test

In the countermanding task, the subjects generated two different types of observable responses: responses despite the presence of a

stop signal (*stop failures*) and responses when no stop signal occurred (*control trials*). It has been shown (for details, see Colonius et al., 2001) that the race model implies a simple ordering of the corresponding observable RT distributions that can be utilized as a model test. Specifically, the (cumulative) distribution of stop failures, for any given SSD, has to lie above the (cumulative) distribution of RTs in the control trials. Formally,

$$P[T \leq t \mid \text{stop signal presented } t_d \text{ msec after go signal}] \geq P[T \leq t \mid \text{no stop signal presented}] \quad (1)$$

for all $t, t \geq 0$, where T denotes observed RT and t_d stands for SSD. This implies, in particular, that mean stop failure responses should never be slower than mean go signal responses (cf. Logan, 1994).

Results

Only saccades free of blinks and improper fixations were used for further analysis, resulting in the numbers of saccades in each condition (see Table 1). Dependent variables were saccadic latency, amplitude, and peak velocity in the visual and the countermanding tasks and the probability of a response in those trials of the countermanding task in which a stop signal was given. Depending on whether the subject was able to withhold the response to the go signal, the trials were denoted *stop success* trials (subject was able to withhold response) or *stop failure* trials (subject responded despite the stop signal). Trials in the countermanding task without a stop signal were called *control* trials. Sufficiently stable calibration for the analysis of saccadic amplitudes and peak velocities was reached for all the data from Subjects M.R. and P.T., but not from D.L.

Saccadic Reaction Times

Table 1 compares overall mean latencies in the visual task, control trials, and stop failure trials for each subject. Note that Subjects M.R. and D.L. were able to maintain their response speed in the stop signal experiment at the level reached in the visual task sessions, whereas Subject P.T. was substantially slower in the stop signal experiment than in the visual task. Latencies in stop fail-

Table 1
Number of Measurements Included in Data Analysis and Mean Reaction Time (RT, in Milliseconds; With Standard Errors of the Means) for All Data Sets of the Visual Task and for the Control and Stop Failure Trials of the Countermanding Task

Subject	Measure	Visual Task	Countermanding Task	
			Control	Stop Failure
M.R.	<i>N</i>	370	2,075	348
	Mean RT	210	213	227
	<i>SEM</i>	±1.8	±0.8	±2.4
D.L.	<i>N</i>	369	2,740	406
	Mean RT	221	223	236
	<i>SEM</i>	±2.2	±0.6	±2.5
P.T.	<i>N</i>	387	2,144	313
	Mean RT	202	228	222
	<i>SEM</i>	±1.6	±0.7	±1.2

Note—Visual performance changed after the intervening countermanding task for Subjects M.R. (pretest, 216 msec; posttest, 200 msec) and D.L. (pretest, 226 msec; posttest, 214 msec), but not for Subject P.T. (pretest, 202 msec; posttest, 203 msec).

Table 2
Stop Signal Delays (SSDs) for Each Subject, Percentage and Number of Stop Failure Trials for Each SSD, Mean Reaction Times (RTs, in Milliseconds; With Standard Errors of the Means), and Stop Signal Processing Times (SSPTs) Estimated According to the Integration Method on the Basis of the Race Model

Subject	Measure	SSD 1	SSD 2	SSD 3	SSD 4
M.R.	Delay	30	80	130	
	% stop failure	18.8	44.5	83.5	
	<i>N</i>	45	106	197	
	Mean RT	239	234	221	
	<i>SEM</i>	±8.9	±4.5	±2.7	
	SSPT	146	135	115	
D.L.	Delay	30	120	150	170
	% stop failure	10.7	27.9	58.9	76.9
	<i>N</i>	25	65	136	180
	Mean RT	263	243	235	230
	<i>SEM</i>	±15.2	±7.0	±4.1	±3.2
	SSPT	158	86	76	73
P.T.	Delay	70	100	130	
	% stop failure	7.5	40.8	82.1	
	<i>N</i>	18	98	197	
	Mean RT	231	219	223	
	<i>SEM</i>	±7.8	±2.5	±1.4	
	SSPT	123	119	118	

Mean stop failure latencies decreased with increasing SSD for Subjects M.R. and D.L., with significant differences between the shortest and the longest SSDs (M.R., $p = .02$; D.L., $p = .03$; two-tailed U test), whereas Subject P.T. showed a nonmonotonic pattern, without a significant difference between the first and the third SSD (Table 2).

Inhibition Functions

The percentage of stop failure responses increased with increasing SSD for all the subjects. The probability of inhibiting a response, given a stop signal, is estimated by the relative frequency of successful inhibitions for each SSD t_d . The inhibition functions are plotted separately for each subject in Figure 2.

Distribution Inequality Test

The cumulative distribution of the latencies in control trials constitutes a lower bound for the stop failure latency distributions under the race model (cf. Equation 1). As is apparent in Figure 3, the bound was violated for most SSD conditions. These violations were significant for all SSDs for Subjects M.R. and D.L. ($p < .01$ in each case, Kolmogorov–Smirnov).

Spatial Position Effects

Figure 4 presents probability of inhibition (upper panel) and mean RT (lower panel) as a function of the position of the auditory stop signal relative to the go signal (ipsi- vs. contralateral) separately for each subject. When go and stop signals were presented at the same position, the inhi-

ure trials were significantly reduced, as compared with control trials, for Subject P.T. ($p = .001$, two-tailed Mann–Whitney U test). In contrast to this, M.R. and D.L. exhibited significantly *longer* latencies ($p < .001$, two-tailed U test) in stop failure trials. The latency distributions of visual task and control trials are provided in Figure 1.

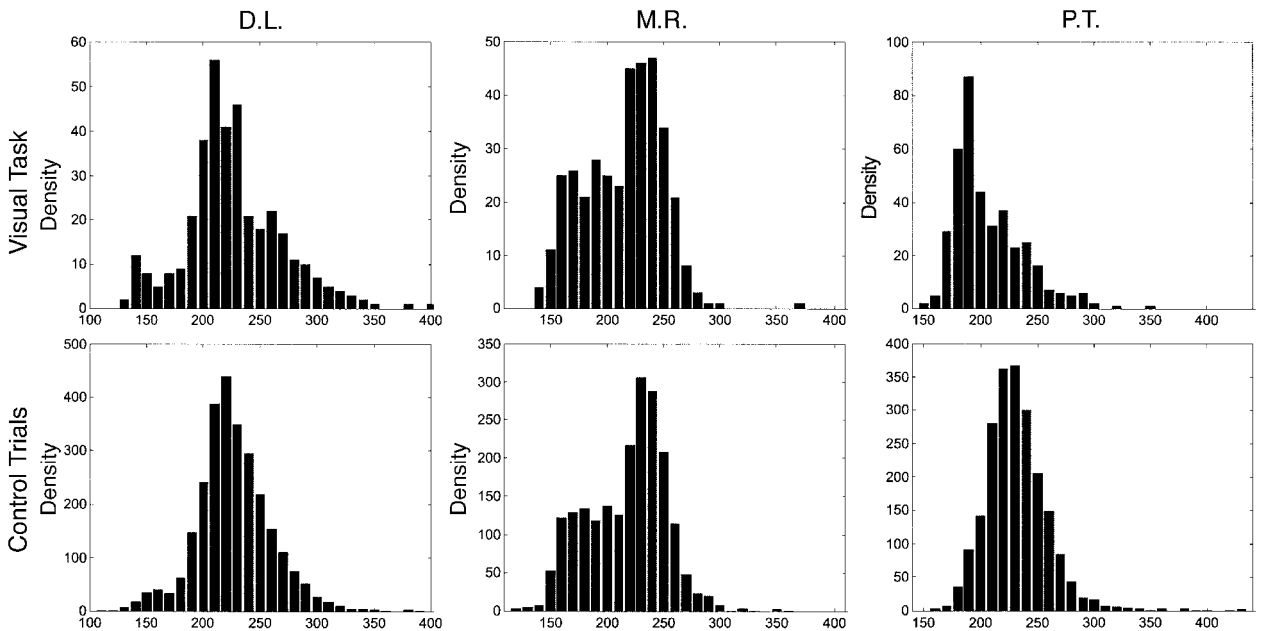


Figure 1. Latency distributions for saccades to visual targets in the visual task and in control trials of the countermanding task, plotted individually for each subject. For Subjects D.L. and M.R., the distributions in both conditions are similar, whereas the control trial latencies of Subject P.T. are delayed relative to those in the visual task.

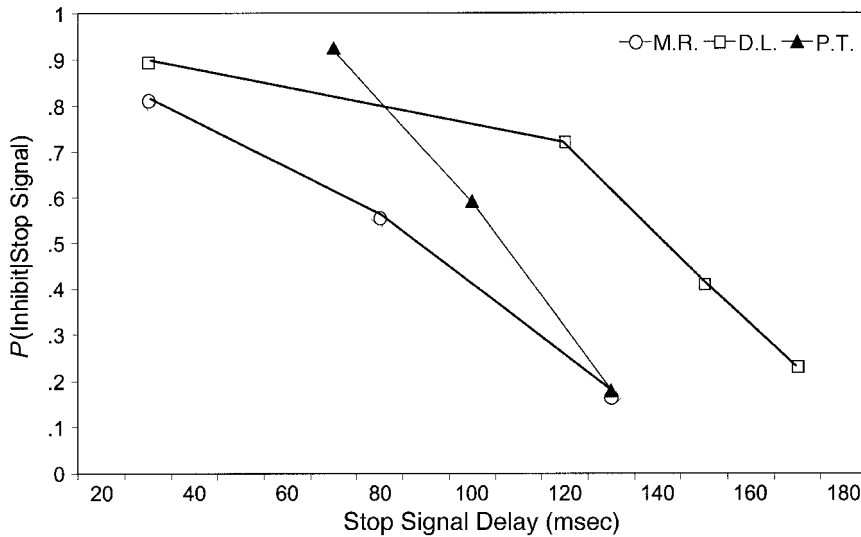


Figure 2. Inhibition functions. For each subject, the probability of saccadic inhibition in stop trials is plotted as a function of stop signal delay. The probability that the response to the target would be inhibited was lower for Subject M.R. than for D.L. and P.T.

bition probability was smaller than that for contralateral presentation. The effect was small, reaching a value of $p = .085$ (Pearson's χ^2 test) by accumulating across subjects. For the latencies, the contralateral stimuli yielded slower mean RTs than did the ipsilateral stimuli. This effect was most pronounced for small SSDs with values of 10–20 msec and vanished for higher SSDs. Owing to the small number of observations for small SSDs, the latency effect was not significant. Moreover, comparing mean RTs in control trials with respect to expected versus non-expected side of the stop signal did not show any effect.

Saccadic Amplitude

The mean saccadic amplitude in stop failure trials was significantly reduced, as compared with amplitudes in control trials (M.R., $p = .006$; P.T., $p = .003$; two-tailed U test). Whereas amplitudes in control trials did not vary with the time interval between go signal presentation and response execution, amplitudes in stop failure trials decreased with increasing temporal distance between the stop signal and the response (Figure 5). Concerning Subject P.T., a comparison of saccades elicited up to 80 msec after stop signal presentation with those elicited more than 140 msec after the stop signal revealed a significant decrease of saccadic amplitudes ($p = .016$, two-tailed U test). For Subject M.R., saccades executed up to 80 msec after stop signal presentation had to be excluded from this analysis. These saccades were clearly hypometric presumably as a result of (unconscious) strategy by the subject. For saccades carried out beyond 80 msec after the stop signal, a significant reduction was found for this subject ($p = .011$) as well. Main sequence characteristics, describing the well-known relatively fixed relationship between the amplitude and the peak velocity of saccades, were preserved in stop failure trials.

Discussion

The most important modification of the countermanding task in this experiment was our capacity to identify the subjects' strategies. Determining individual speed levels in the visual task prior to the actual countermanding task allowed us to gauge the subjects' speed level employed in the subsequent countermanding task. Feedback after each block of trials informed the subjects whether they had been able to follow the instruction to maintain the speed level measured in the visual task. As a result, it became clear that 2 subjects (M.R. and D.L.) could in fact follow the speed instruction in the countermanding task, whereas the third (P.T.) could not fully satisfy the speed instruction (cf. Table 1). This means that Subjects M.R. and D.L. did not delay their responses in expectation of the stop signal—that is, they did not trade speed for success in stopping. Accordingly, for M.R. and D.L., rather small SSDs were employed, as compared with P.T.

Inhibition Between Go and Stop Signal Processing

An important prediction of the race model is that average stop failure RTs are smaller than mean control RTs. However, Subjects M.R. and D.L. showed significantly larger mean stop failure RTs than mean control RTs (14 msec for M.R. and 13 msec for D.L.; $p < .001$; cf. Table 1). Moreover, according to the model, stop failure RTs should increase with an increase of SSD. Again, Subjects M.R. and D.L. showed the opposite pattern—that is, stop failure RTs decrease with SSD—whereas P.T. showed a nonmonotonic pattern. These effects on the level of the means are reflected in more detail in Figure 3, showing the violations of the distribution inequality, most pronounced for small SSDs (Equation 1). In line with this is the following observation. Assuming

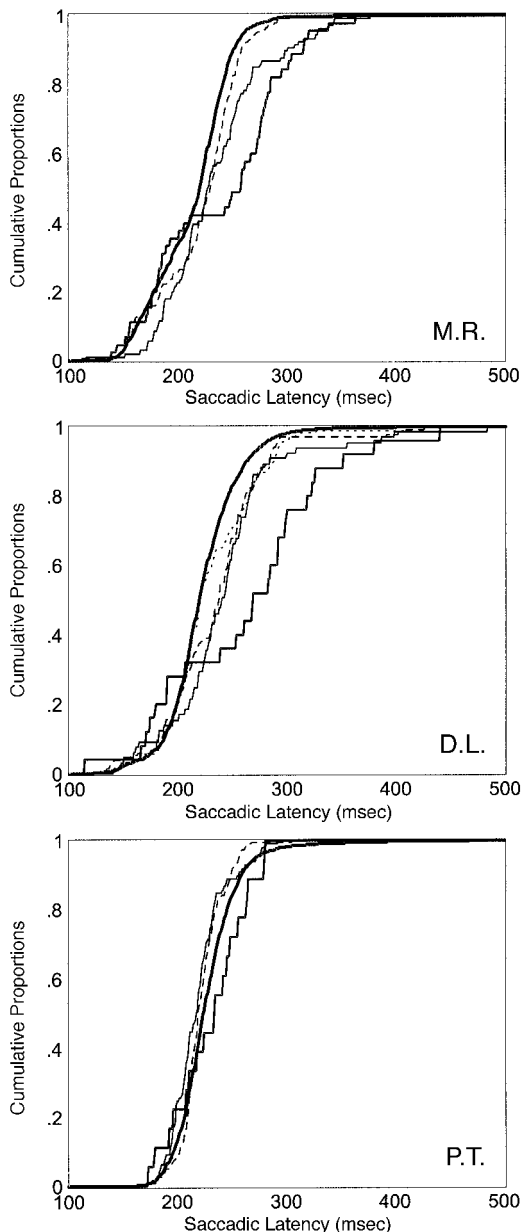


Figure 3. Test of the lower boundary. Cumulative distribution functions of reaction times in stop signal delay (SSD) conditions should not cross the lower bound represented by the cumulative distribution function of reaction times in the control condition (thick line, control condition; medium line, SSD1; thin line, SSD2; dashed line, SSD3; dotted line, SSD4).

that the effect of a response delay is a shift of the distribution of control responses to the right, the estimates of SSPT should still be relatively invariant over SSD. However, for Subjects M.R. and D.L., we found estimates of SSPT to decrease quite drastically over SSD (see Table 2).

The fact that deviations from the race model's predictions decreased with the temporal distance between the go and the stop signals supports our hypothesis of an inhibitory influence between the two: Presentation of the

stop signal decelerates the processing of the go signal. Thus, the stop signal might prolong RT while processing of the stop signal is not yet completed. Conversely, the processing of the visual stimulus already in progress might delay processing of the stop signal. As a result, the inhibition of the saccadic response would be delayed, and saccades with relatively long latencies would be executed. In both cases, the effect would be the same, in the sense that the resulting stop failure latencies are too long to be compatible with the race model.

The delay in stop signal processing is reminiscent of the *psychological refractory period* found in the dual-task paradigm: When two stimuli are presented in rapid succession and have to be responded to with different actions, the response to the second stimulus is usually delayed (see Pashler & Johnston, 1998). Although the stop signal paradigm differs from the dual-task paradigm in that the second stimulus (the stop signal) does not require an overt response but the inhibition of the response to the first stimulus, note that, in both paradigms, a distinct response to when each stimulus presented closely in time is required. Thus, both tasks could be susceptible to similar limitations of central processing resources. Moreover, increasing the interstimulus interval may diminish the interference effect. In a similar vein, Logan and Burkell (1986) compared performance in the stop paradigm (letters as go signal, tones as stop signal) with performance in a dual-task and a change paradigm using the same stimuli and delays, in order to test for differences in interference between the three paradigms. They observed small but consistent evidence for nonindependence in terms of an upward concavity in their estimated SSPTs as a function of increasing SSD. They also found longer SSPTs in the change paradigm than in the stopping paradigm. Both findings were interpreted as possible refractory effects, which, however, were small and negligible, as compared with the much larger interference that occurred in the dual-task paradigm.

Using visual go and stop signals, Hanes and Carpenter (1999) found slightly prolonged stop failure RTs for saccadic eye movements. As has been reported here, the discrepancy between model predictions and data was strongest for small SSDs. They hypothesized a downstream inhibitory process that, in some trials, slows down but does not completely abolish a saccade that is being prepared. Note, however, that it remains unclear why this mechanism should apply specifically to trials with very brief SSDs.

Saccade Trajectory Effects

The analysis of saccadic amplitudes provides further evidence for a violation of the independence between go and stop processes. The observation that amplitude size decreased with an increasing time interval between presentation of the stop signal and saccade execution shows that the response decision is not just between execution or stopping. Rather, the movement itself is altered under the influence of the stop signal. Note that the change in movement amplitude cannot simply be attributed to an

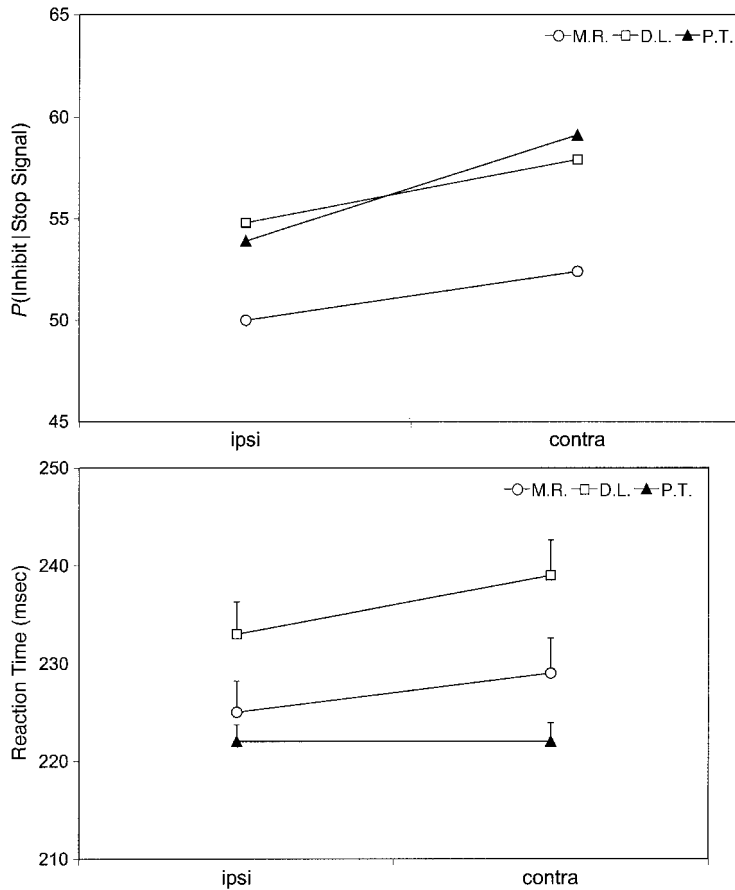


Figure 4. Probabilities of inhibition (upper panel) and mean reaction times (lower panel) for ipsilateral and contralateral presentation of visual go and auditory stop signals. Both probabilities of inhibition and reaction times were lower for ipsilateral stimulus presentation. For reaction times, one standard error of the mean is indicated.

attempt to stop the movement during execution, since (in contrast to hand movements) eye movements, at least of a size below 10° – 15° , are programmed in advance and are not modifiable during movement execution (Findlay & Walker, 1999). Moreover, programming of the saccade starting time and of the end position of the eyes are assumed to be controlled by two distinct neural pathways; the *when* and the *where* pathways (see Findlay & Walker, 1999; Van Opstal & Van Gisbergen, 1989). When the *when* pathway triggers the saccade onset, the spatial coordinates present in the *where* pathway at that specific point in time are read out and executed. Our amplitude data suggest that, when the time interval between stop signal presentation and execution of the movement is short, the *where* pathway is dominated by the visual target coordinates, since the saccadic amplitudes did not differ from those in control trials. However, when the time interval increases, the stop signal's influence on saccadic amplitude increases. This gradual decrease of saccadic amplitude (presumably, owing to population coding of saccadic movement parameters) seems hardly

reconcilable with the race model idea, which suggests an all-or-none effect on the *where* pathway, depending on the winner of the race.

Spatial Position Effects

The observation that responses to the go signal, when no stop signal occurred, were not faster when the go signal came from the side where the stop signal was expected is consistent with the hypothesis that there is no general shift of spatial attention toward the direction of the stop signal position.

The inhibition data indicate, however, that the go signal was more difficult to countermand when the stop signal came from the same side as the go signal. This interesting result is in line with a host of data on visual–auditory interaction in saccades. In fact, in a *focused attention task* in which subjects had to move their eyes to a visual target while a nontarget auditory stimulus, presented closely in time and in space, could be ignored, it has been shown that saccadic responses are faster than in a unimodal visual condition (e.g., Colonius & Arndt,

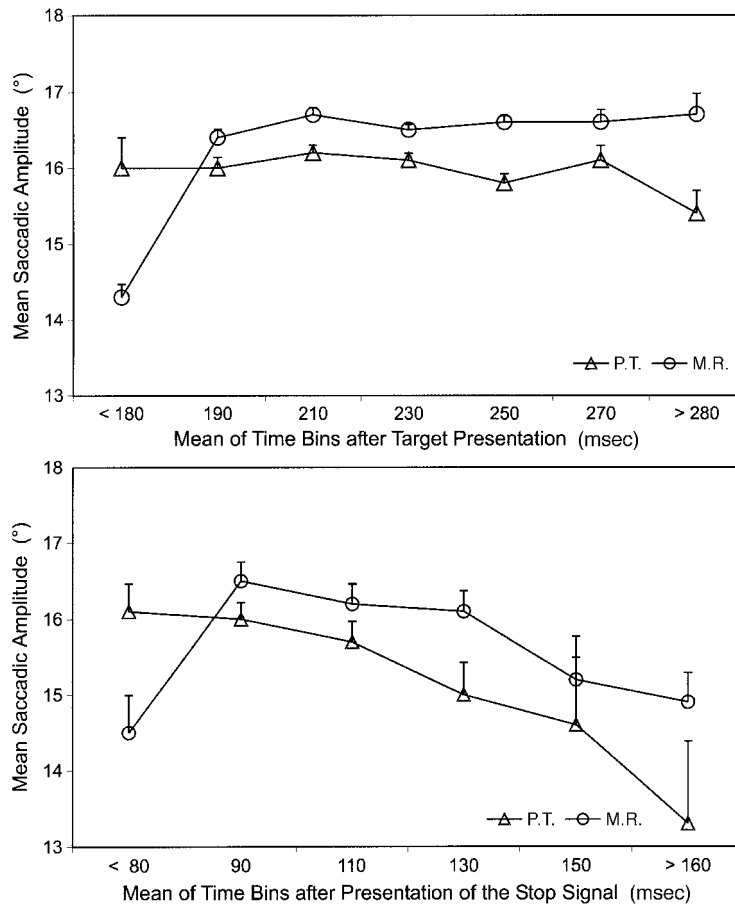


Figure 5. Mean amplitudes of saccadic responses in control trials (upper panel) and stop failure trials (lower panel) in different periods of time. For each time bin, one standard error of the mean is indicated. Periods of time are defined with respect to the presentations of the go stimulus and the stop signal.

2001; Frens, Van Opstal, & Van der Willigen, 1995). In particular, the amount of facilitation decreased with the distance between the visual target and the auditory “distractor.” Thus, in the countermanding task, the response to the visual target could similarly be facilitated by the occurrence of the stop signal at a position close to the visual target, thereby making it more difficult to countermand the go response. This hypothetical explanation does not deny the different functional roles of the auditory stimulus in the focused attention and the stop signal tasks. However, before the auditory stimulus can be interpreted as a stop signal (requiring a cortically based decision process), it has to be detected; and in this early stage, its function may be similar to the nontarget in the focused attention task. Note that this hypothesis is consistent with the observation that the spatial position effect on the latencies was most pronounced at small SSDs.

CONCLUSION

The violations of the race model’s predictions observed in our data suggest that there exists an interference be-

tween the processing of the go and the stop signals, contradicting the model’s independence assumption. Although a number of previous studies have seen some indication of this interference, this study elucidates this fact by identifying and, in 2 subjects, abolishing a response delay strategy that normally conceals the interference effect. Nonetheless, further behavioral and neurophysiological research will be necessary to fully understand the nature of the interference process.

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