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Visual-tactile saccadic inhibition

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Abstract In an eye movement countermanding paradigm it is demonstrated for the first time that a tactile stimulus can be an effective stop signal when human participants are to inhibit saccades to a visual target. Estimated stop signal processing times were 90–140 ms, comparable to results with auditory stop signals, but shorter than those commonly found for manual responses. Two of the three participants significantly slowed their reactions in expectation of the stop signal as revealed by a control experiment without stop signals. All participants produced slower responses in the shortest stop signal delay condition than predicted by the race model (Logan and Cowan 1984) along with hypometric saccades on stop failure trials, suggesting that the race model may need to be elaborated to include some component of interaction of stop and go signal processing.

Introduction

Voluntary inhibition of action is an everyday phenomenon in which a person responds to changes in his or her goals or circumstances. The call of a linesman causes a tennis player to refrain from carrying out the planned stroke, and warning lights are used in cockpits and other complicated environments to signal that the user should discontinue an inappropriate activity. When successful, this kind of fast inhibition of a movement is often implemented without much contemplation over the

cognitive mechanics involved. This underlying functionality has been explored using the stop signal or countermanding task (e.g., Vince 1948; Lappin and Eriksen 1966; Logan 1994), a variation and extension of the widely used go/no-go paradigm. In the go/no-go task inhibitory behaviour is explored by presenting two classes of trials: go trials with an imperative stimulus requiring a response, and no-go trials with a different stimulus requiring no action to be taken (e.g., Donders 1868/1969). As the requested response suppression on no-go trials is often highly successful in these experiments, potentially interesting information about failed inhibition is rarely obtained. In contrast the stop signal task provides this additional information by securing the acquisition of sufficient amounts of failed as well as successful inhibition data. In the majority of trials participants are required to respond quickly and reliably to the go stimuli, while in a minority of trials—the stop trials—a stimulus calling for withholding the response is presented at various delays. This allows for a comparison of responses made on the go trials with those performed under different levels of urgency to inhibit, induced by the stop stimulus occurring after the different delays.

Research using the countermanding paradigm in various settings has yielded a model framework describing the processes involved in voluntary inhibition, as well as some general conclusions about these processes (Logan 1994; Logan and Cowan 1984). For example, stopping is regarded as a modality-independent operation (Logan 1994) involving the frontal lobe (M. Rieger, unpublished dissertation), and as requiring a surprisingly invariable amount of time to act (Naito and Matsumura 1994). The central tenets of that race model framework are that the cognitive events started by the go and stop signals run in parallel and independently of each other, and that the outcome on a given stop trial (either response or successful inhibition) depends solely on which process first reaches some (not necessarily a common) threshold. These assumptions, regarded by some as critical to the validity of the race model

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(Paré and Hanes 2003; Kok et al. 2004), lead to quite detailed predictions about the reaction times (RTs) obtained when participants fail to inhibit despite the presentation of a stop signal. Interestingly, the assumptions also enable the estimation of inhibition performance in terms of the duration of the stopping process, the stop signal processing time (SSPT), based on the means and distribution functions of the RTs obtained.

The RT predictions following from the race model have usually been validated by experimental data including a recent study using fMRI measurements to unravel the underlying neural circuitry (Curtis et al. 2005). However, in most studies the performance of the participants on the go trials has not been tested separately as well as in the context of the stop trials. This may allow for unnoted strategic trading of response speed for inhibition success, interfering with the assumed context-invariant processing. Moreover, small but persistent violations of model predictions following from the assumption of stochastic independence between the go signal and SSPT have been observed. Specifically, the RT distributions obtained on the stop failure trials in conditions with very short delays tend to have elongated slow tails, with 5–15% of the responses violating the stochastic independence (Logan and Cowan 1984; Hanes and Carpenter 1999; but see, e.g., Hanes and Schall 1995). This has also been observed when the above-mentioned trading strategy has been controlled for (e.g., Colonius et al. 2001; Özyurt et al. 2003).

Early stop signal experiments mostly involved manual responses to visual go signals, and visual or auditory stop signals (for a review see Logan and Cowan 1984). In recent years, attention has increasingly turned to the inhibition of saccadic eye movements (e.g., Hanes and Carpenter 1999; Logan and Irwin 2000; Paré and Hanes 2003). Several saccadic stop signal studies using the visual go and stop signals have produced notably fast inhibition processing, with an estimated SSPT as short as 100 ms. Schall and Thompson (1999) suggested that this was due to the stop signal being presented centrally on the fovea. A foveally presented stimulus could contribute to saccadic inhibition in at least two ways: the intended, task-relevant form of inhibition, and a bottom-up interference with saccadic programming which could delay or even inhibit the motor command. Asrress and Carpenter (2001) did not find a difference between the effectiveness of central and peripheral stop signals, but found that combining the two stimuli was more effective than either stop stimulus alone. They suggested, as had Schall and Thompson (1999) and Hanes and Carpenter (1999), that experiments using go and stop signals from different sensory modalities should be conducted to clarify which effects are purely inhibition related and which are due to the particular stimulus and response modalities used.

Cabel et al. (2000) employed three different stop signals, a foveally presented visual stimulus, an auditory stimulus, and a signal comprising both stimuli. They

found longer saccadic SSPTs for auditory than for visual stop stimuli, with the combined stop signal being the most effective. They concluded that the visual stop signal instigated several inhibitory processes (based on foveal, visual stimulus onset, and nonfoveal instructional information, respectively), whereas the power of the auditory signal relied on the instructional information only, and the combined signal allowed for a statistical facilitation of inhibition processing. However, a comparison of SSPT estimations across stop signal experiments using either visual or auditory stop stimuli shows that auditory stop signals generally lead to shorter SSPTs than visual ones. The size of the effect indicates no general modality differences in the efficacy of the stop signal when differences in transmission latency are taken into account. The opposite finding by Cabel and colleagues could be explained by the particular design of that experiment rather than an actual modality difference.¹

The present study extends the aforementioned tests of the modality-independence of the stopping process by introducing tactile stop signals. If the modality of the stop signal does not influence its effectiveness, the RT data obtained should be in line with results from experiments using visual or auditory stop signals. In addition to this test of the modality-independence of stop signal processing, participants' performance on the go task was tested separately to disclose any strategic speed–accuracy tradeoff. Finally, the data obtained were tested against predictions from the race model of Logan and Cowan (1984).

Methods

Design

In the present experiment the participants were presented with visual go signals and, in 25% of the trials, additionally with tactile stop signals. In the go trials, the initial central fixation point was followed, after a variable interstimulus interval (gap), only by a go signal either on the left or on the right. The task of the participant was to perform a rapid saccade towards the go stimulus. In the stop trials, the go stimulus was followed by a vibratory stop signal presented simultaneously to both hands at one of the three different stop signal delays (SSDs). In these trials, the participant was required to inhibit any eye movement.

The participants were first trained on blocks containing only go trials until their performance on this task

¹The experiment by Cabel et al. (2000) differed from the general stop signal design in that the go stimuli always appeared at the same delay from the time when the participant initiated the trial. In addition, the auditory stop signal was delivered from a speaker 2 m above the head of the participants, while visual stimuli were presented on a monitor in front on them. Thus, the modality-dependent effect found may have been due to the trial design, spatial features of the stimuli, or both.

stabilized around some mean RT value. Then stop trials with three randomly chosen SSDs were interspersed with the go trials, and the SSDs were adjusted to produce three distinct probabilities of successful inhibition (approximately 20, 50, and 80%). During this adjustment procedure and the subsequent stop signal experiment participants were urged to focus on performing well on the go trials, in an attempt to match the mean RT value obtained in the preceding go training. Once these criteria had been reached, or the participant ceased improving his or her RT performance, each participant completed a minimum of 3,000 trials in the stop signal experiment over a number of sessions.

Participants

Three participants were tested, two males (HB, age 33 years; DS, 20 years) and one female (PB, 20 years). All had normal or corrected-to-normal vision and right eye dominance. The experiment was carried out with the informed prior consent of the participants, who were compensated for their participation partly with compulsory subject hours and partly with money paid out after the last session. The ethical standards described in the 1964 Declaration of Helsinki were followed.

Apparatus and stimuli

The participant was seated in a darkened, sound-attenuated room with the head positioned on a chin rest and the elbows and lower arms resting comfortably on a table. The fixation point and the visual stimuli were red light emitting diodes (LEDs) (5 mm, 8 cd/m²) situated on the table 60 cm in front of the participant, the fixation point in the centre and the go LEDs 10° to the left and right of it, respectively. The fixation point was presented for 1,000 ms and the duration of the visual go stimuli was 500 ms. The tactile stimulation, which had a frequency of 50 Hz and a duration of 500 ms, was

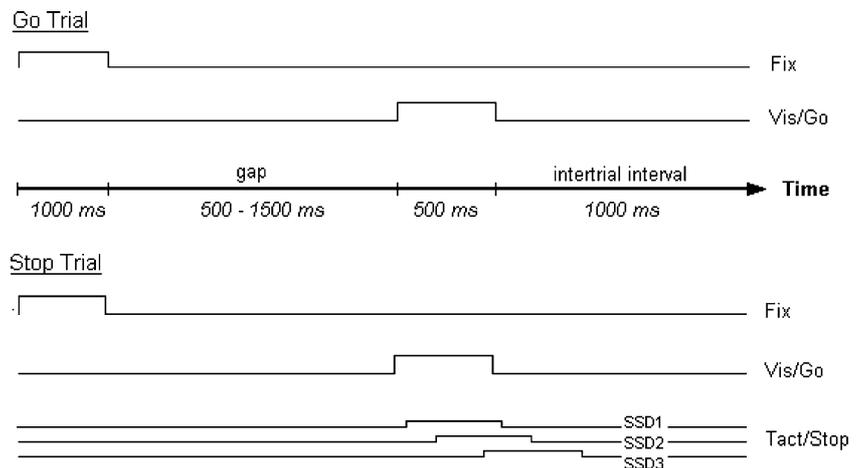
generated by two silent vibration exciters (Brüel and Kjær, Nærum, Denmark) placed on bases situated under the table. Positioned in each shaker was a metal rod extending through a hole in the table approximately 2 cm above the surface. On each rod was a wooden ball of 14 mm diameter, which rested in the palm of the participant and transmitted the vibration to the hand. Eye movements were recorded at a rate of 250 Hz using the infrared light video system EyeLink (Sensomotoric Instruments, Berlin, Germany), which has a gaze position accuracy of <0.5° average. One PC controlled the stimulus presentation, and two other interlinked PCs controlled the EyeLink program.

Procedure

The experimental procedure was similar for the go trial training and the stop signal adjustment procedure and experiment. One block consisted of 100 (in the go training) or 120 trials (in the stop adjustment and experiment; 90 of which were go and 30 stop). Each trial started with the presentation of the central fixation point. After this, there was a variable interval during which no stimuli were presented. Then the go stimulus, one of the go LEDs (left or right), came on. In the go trials, the go stimulus was followed by an interval of 1,000 ms after which the next trial began. However, in the stop trials the go stimulus was followed by the stop stimulus, presented to both hands after the appropriate SSD relative to the onset of the go signal. Only after the presentation of the stop signal did the 1,000 ms intertrial interval start. The go and stop trials are shown schematically in Fig. 1.

Participants were instructed to keep their gaze on the fixation point (or, in the intervals, the location where the fixation point had previously been), and to move their eyes to the go target as quickly as possible when it appeared. However, they were to inhibit this movement and continue fixating in the event of a stop signal occurring. They were informed that it would not be

Fig. 1 Schematic representation of the stimulus configuration of go training (*above* only) and of the stop signal experiment (*above* and *below*). Note that on each stop trial (*below*) the stop signal was presented at one of the three different delays relative to the go signal



possible to do this on all stop trials, but that they should nonetheless try to be as fast as possible in their responses and not slow down in expectation of a possible stop signal.

In the go training, trials were sampled in random order from a population of 20 trials, each with a different, randomly chosen length of the gap between the fixation point and the go signal (range: 500–1,500 ms). In the stop experiment, all 120 trials were prepared before the onset of the experiment and only the order of presentation of trials was randomized between blocks. For these trials, five different gaps with the same range as in the go training trials were used, each with equal probability. Additionally, in the stop trials the three equiprobable SSDs for each participant were set based on participant performance during training of the stop task. The SSDs used ranged from 30 to 170 ms.

Thus, each of the 30 stop trials had a unique combination of gap length, SSD length (three levels: individually set), and direction of required response (two levels: left, right). The 90 go trials that were control trials in the stop experiment were made by reproducing the combinations of gap length and direction of required response so that all levels of these factors were equally probable. Hence, each unique stop trial was matched with three similar go trials, so that for all questions of interest the probability of a stop trial was 25%.

Results

For each participant, the 300 trials of go training following stabilization of performance on this task were recorded. A total of 2,872 (DS), 3,901 (HB), and 4,243 (PB) trials from the stop experiment were accepted for further analysis. For both the go and the stop sets the data were collapsed across the direction of eye movement response. The dependent measures were saccadic latency and amplitude for both the go condition and the three stop conditions, as well as probability of response for the latter. Trials containing blinks, improper fixations,

responses in the wrong direction, saccades with amplitudes larger than 30°, guesses (RT latency shorter than 70 ms), or responses which were too slow (RT latency longer than 500 ms) were excluded from further processing. In the go trials, movements smaller than 2° were also considered as improper fixations, while these were classified as correct inhibitions in stop trials. Whereas go trials were either accepted or rejected based on the above criteria, stop trials resulted in successful inhibition, accepted response (stop failure), or rejection. The numbers of trials in each category for the three participants tested are shown in Table 1. Also shown are the lengths of delay used for each participant.

Inhibition functions

The basic requirement for a satisfactory stop signal is that it enables successful inhibition on some proportion of stop trials. The Logan–Cowan race model further predicts that the probability of success depends on the length of delay between the go and stop signals: the longer the delay, the smaller the chance of inhibition success. By comparing the percentages of successful inhibition (of all accepted trials) across the different stop conditions for the participants in Fig. 2, it can be seen that these requirements were fulfilled by the tactile stop signal. The likelihood of successful inhibition dropped from approximately 80% for the condition with the shortest delay to approximately 20% for the longest delay, with intermediate delays producing probabilities around chance (50%). This monotonic pattern was evident for all three participants.

Saccadic reaction times

Table 2 compares the average reactions of each participant from the go training with those from the stop experiment (i.e., go control trials, stop failure trials in each delay condition of the stop experiment, and stop

Table 1 Numbers of trials in the go training and each category of the stop experiment for each of the three participants, along with the individual stop signal delays used

Participant	Go training	Stop experiment			
		Go control	SSD1	SSD2	SSD3
DS			30 ms	110 ms	170 ms
Responses	291	2,155	48	129	213
Inhibited	N/A	N/A	175	117	35
Rejected	9	95	27	4	2
HB			30 ms	90 ms	110 ms
Responses	296	2,921	70	206	252
Inhibited	N/A	N/A	252	122	78
Rejected	4	49	8	2	0
PB			30 ms	110 ms	170 ms
Responses	297	3,167	59	164	303
Inhibited	N/A	N/A	298	195	56
Rejected	3	73	3	1	1

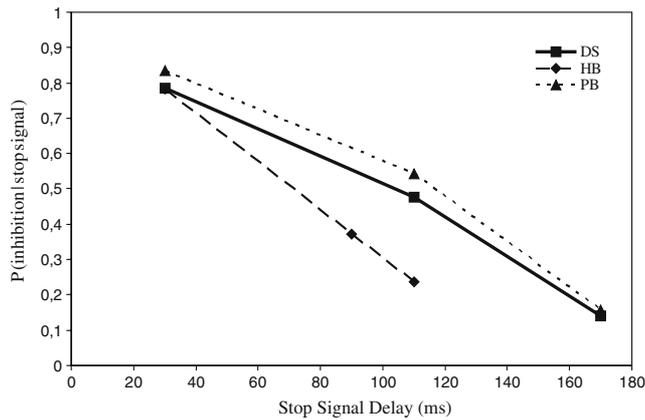


Fig. 2 The inhibition functions of the three participants

failures overall). The mean saccadic RTs are shown in the upper panel. HB was slower than either PB or DS on the pure go task, but was able to keep his average go response latency at the go training level in the stop signal experiment. In contrast, PB and DS were 59 and 66 ms slower on average, respectively, at go responses in the context of the stop trials relative to their average speed of responding before the introduction of the stop trials. All participants had faster average response times for each of the stop conditions than for the go control trials.

The slower go responses exhibited by DS and PB in the stop experiment were significantly different from the responses they performed during go training ($P < 0.001$ for both participants, two-tailed t -tests). The difference obtained for HB was nonsignificant. A one-way ANOVA was performed on the RTs in the stop experiment conditions separately for the data from each participant. For DS, it revealed highly significant differences among the conditions ($P < 0.001$). Post-hoc tests showed that the first ($P < 0.05$, Tukey-HSD) and the second ($P < 0.01$) delay condition data had significantly faster means than the go control mean. Highly significant differences were also found between the RT means in the stop experiment data from PB ($P < 0.001$). Post-hoc tests established that two of the delay conditions, SSD2 ($P < 0.001$) and SSD3 ($P < 0.05$), had significantly faster means than the go control condition. The ANOVA on

HB's data also found significant differences among the mean RTs ($P < 0.01$), of which only the comparison of go control and the last delay condition was significant in the post-hoc tests ($P < 0.05$).

Saccadic amplitudes

The lower panel of Table 2 shows the average sizes of the saccades in each condition grouped by participant. For all participants the mean sizes of the eye movements performed under different stop conditions were smaller than the mean in the go condition of the stop experiment. Except for the longest delay condition for PB, the pattern was that shorter delays lead to shorter saccades.

Subjecting the amplitude data to statistical testing revealed significant differences for all participants. Between the go training and the subsequent go control trials the saccades made by DS got significantly larger ($P < 0.001$, t -test), those from HB got smaller ($P < 0.01$), and those from PB did not show a significant change in size.

One-way ANOVAs on the saccadic amplitudes across stop experiment conditions proved significant for all participants, with the data from DS and HB showing very high levels of significance ($P < 0.001$ each), and that from PB only just proving significant ($P < 0.05$). For DS, post-hoc tests showed that the saccadic amplitudes in the SSD1 condition were significantly smaller than both those in the SSD2 ($P < 0.05$, Tukey-HSD) and the SSD3 ($P < 0.01$) conditions, as well as those on the go control trials ($P < 0.001$). The difference between mean saccadic amplitudes in the SSD2 and in the go control condition was also significant ($P < 0.01$). The go saccadic amplitudes produced by HB were significantly larger than SSD1 ($P < 0.001$), SSD2 ($P < 0.001$), or SSD3 ($P < 0.001$) saccades. In addition, the difference between the SSD3 and the SSD1 saccadic sizes was significant ($P < 0.01$). None of the post-hoc comparisons for PB showed significant effects.

A direct comparison between the amount of concurrent go and stop processing and the size of the resulting saccade is made for each participant in Fig. 3. Go training data are plotted as a solid line, and go control

Table 2 Mean saccadic reaction times (upper panel; in ms) and mean saccadic amplitudes (lower panel; in degrees of visual angle) of the three participants in each condition and across the stop conditions

Participant	Go training	Stop experiment				
		Go control	SSD1	SSD2	SSD3	All three delays
Saccadic reaction times						
DS	154 (2.5)	220 (1.3)	194 (12.9)	199 (5.4)	213 (3.9)	206 (3.2)
HB	218 (2.0)	220 (0.7)	218 (7.2)	214 (2.5)	213 (2.0)	219 (0.6)
PB	166 (1.3)	225 (0.8)	221 (7.6)	209 (2.5)	217 (2.3)	215 (1.8)
Saccadic amplitudes						
DS	9.4 (0.0)	12.0 (0.1)	9.8 (0.6)	11.1 (0.3)	11.5 (0.2)	11.2 (0.2)
HB	11.9 (0.1)	11.6 (0.0)	10.4 (0.3)	10.9 (0.2)	11.1 (0.1)	10.9 (0.1)
PB	12.2 (0.1)	12.3 (0.0)	12.0 (0.2)	12.2 (0.1)	12.1 (0.1)	12.2 (0.1)

Standard errors of the means are indicated in brackets

data as a dashed line. Each data point indicates the mean amplitude of saccades in a 30-ms time bin centred around the RT shown (except the first and the last data points, which include corresponding outliers). The dotted line plots the stop failure data pooled across the delay conditions, with the appropriate length of delay subtracted from the RTs recorded. Hence, the dotted trace shows the relation between the concurrent go and stop processing and the amplitude, as above grouped into time bins of 30 ms and averaged over the amplitudes of the saccades in each bin. The data from DS and HB show substantially hypometric fast saccades in both go control and stop conditions and more similar mean amplitudes across bins with slower movements. For both participants, amplitudes also tend to decrease with growing time lapse from the go or stop signal in the stop failure condition (except for the last bin of stop failures by HB). Standard errors are, however, quite large in the later time bins. PB's saccadic RT versus amplitude data is remarkably similar across both tasks and time bins. She showed no effects of the duration of go processing, nor of the duration of concurrent go and stop processing, on the sizes of her eye movements.

Stop signal processing times

Following the Logan–Cowan race model, the effectiveness of the stop signal was assessed by using the means and distribution functions of the RTs obtained to estimate the SSPT. Using the method of averaging across the delays (of several methods reviewed by Band et al. 2003), the estimates for the SSPTs in this experiment were 91 ms (standard error = 6.0) for participant DS, 139 ms (4.2) for HB, and 110 ms (14.7) for PB.

Distribution inequality tests

For a rigorous test of the RT data against the predictions of the Logan–Cowan race model, the individual saccadic response times obtained from the three partic-

ipants in the different conditions were inspected. The cumulative distribution of stop failure RTs was plotted separately for each delay condition. Under the terms of the race model, this has a lower bound, which is the distribution of the control go trial RTs:

$$P(T \leq t | \text{stop signal at } t_d \text{ ms after the go signal}) \geq P(T \leq t | \text{no stop signal})$$

for all $t, t \geq 0$, T being the observed RT and t_d the delay used. Likewise, an upper bound for each delay condition is constituted by this go RT distribution divided by the probability of stop failure at that particular delay (see Colonius 1990).

Figure 4 shows the cumulative distributions of the RTs for each delay condition for the three participants. In each subfigure, the solid line represents the stop failure responses under that delay, the dotted line shows the lower bound, and the dashed line marks the upper bound. As can be seen in the graphs, the accumulated stop failure responses do not violate the upper bound in any condition of any participant. However, the lower bound is violated by the slowest portion of the data in the shortest delay condition for all the three participants (subfigures in upper row).

Effects of concurrent go and stop signal processing on saccadic amplitudes

Colonius et al. (2001) and Özyurt et al. (2003) reported findings of hypometric saccades on stop failure trials, and interpreted these as evidence of the stop signal affecting the dynamics of the ongoing saccade, in contradiction with the context-invariance of the race model. More specifically, in their data the length of time which passed on stop failure trials between the stop signal presentation and the response was correlated with the decrease in saccadic amplitudes, compared to amplitudes on the go trials. They suggested that stop signal processing might affect saccadic processing, and that increasing concurrent go and stop processing would accumulate this effect. In both studies, the fast saccades performed by several participants had extremely reduced

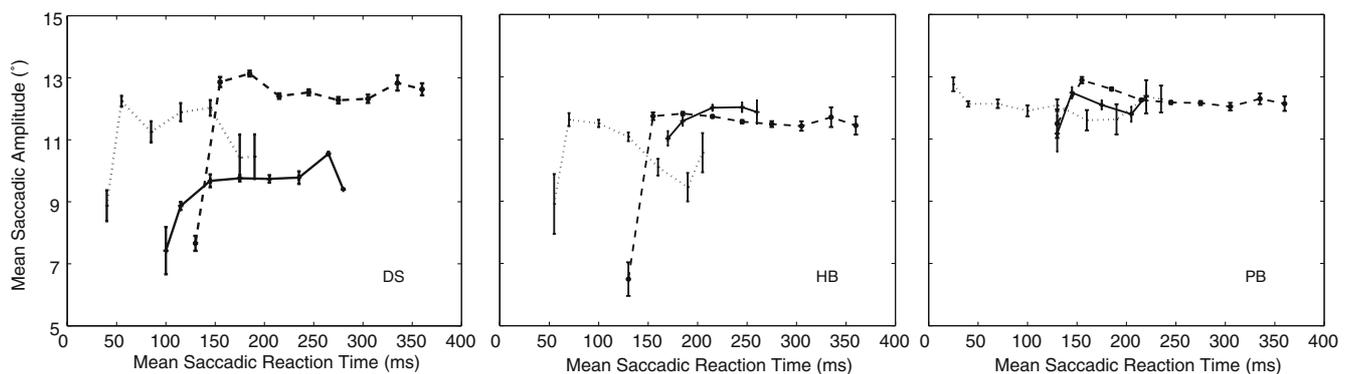


Fig. 3 Mean amplitudes of saccades (and standard errors of the means) for each 30-ms time bin of go training (*solid*, relative to the go signal timing), go control (*dashed*, relative to the go signal), and stop data (*dotted*, relative to the stop signal) of the three participants

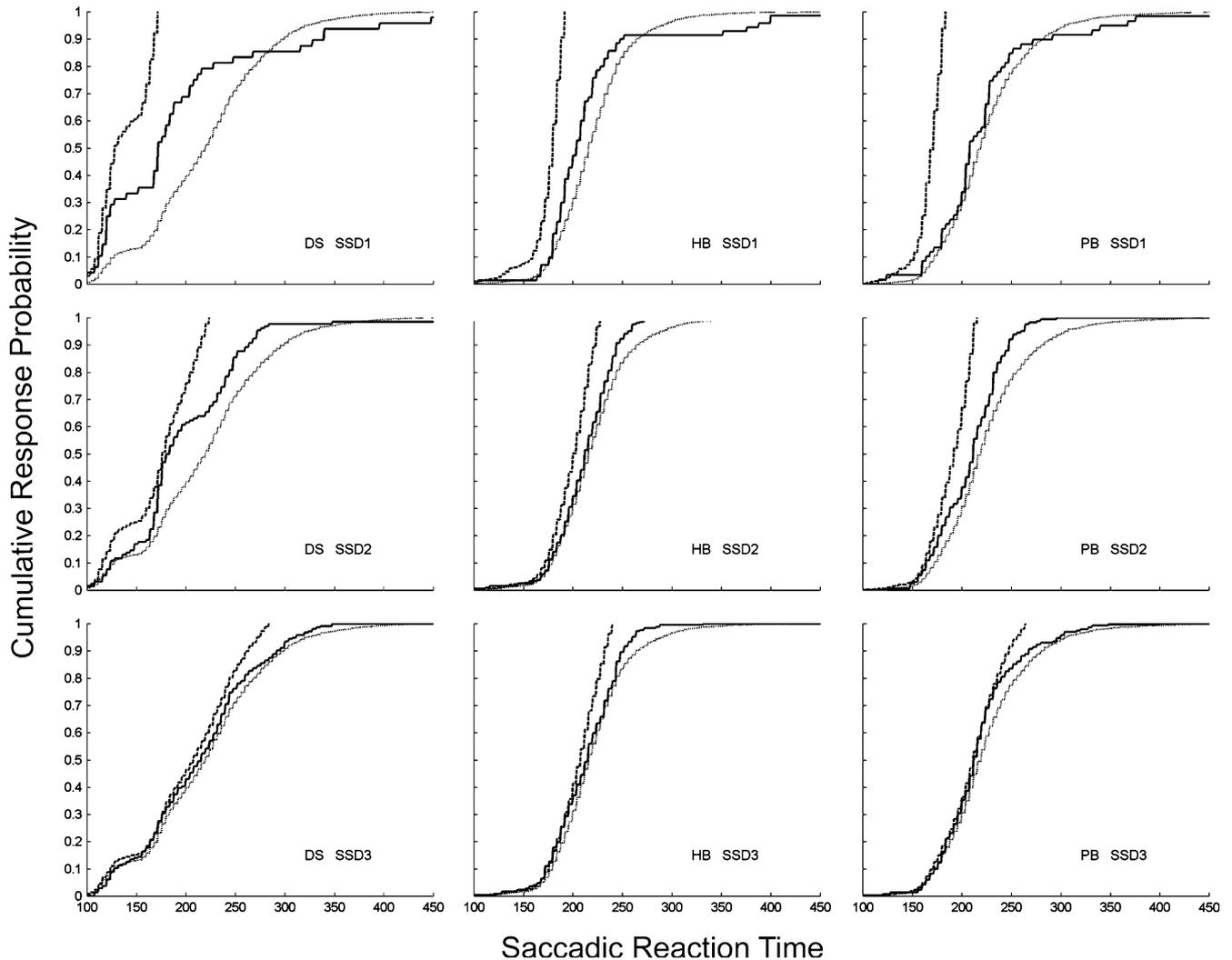


Fig. 4 Distribution inequality tests for reaction times from the three delay conditions for each of the three participants. The recorded responses are shown by the *solid*, the lower bound of the distribution by the *dotted*, and the upper bound by the *dashed* trace

amplitudes, which was interpreted as strategic responding at a time when the presentation of the stop signal was likely.

Discussion

The data demonstrate that the tactile stimulus was an effective stop signal in that participants were able to inhibit successfully on a proportion of those trials in which this was required. This was true for all the three participants tested. In agreement with race model predictions, the probability of successful stopping was reduced with longer delays between the go and stop signals, and this proportion diminished with increasing SSD.

The race model predicts that the mean RT latencies in the stop failure trials should stay below that of the control go trials. In addition, mean RT should increase with the duration of the delay, approaching but not exceeding the go mean RT. Supposing that the go and

stop processes are indeed invariant of the context introduced by the other process, there should be no difference between RTs on the go trials in the training context and those in the stop experiment.

When considering only the mean RTs of the different stop experiment conditions, the data from DS corresponded to the predicted pattern. His slowest mean RT was found in the go condition, and those in the delay conditions grew with increasing delay. PB was unexpectedly slow on the first delay condition. Although her other delay conditions produced significantly faster mean RTs than the go responses, the first delay condition (which should be the fastest) was only marginally, and not significantly, faster than the go control. The third participant, HB, also produced faster mean RTs in the delay conditions than on the go control trials, but contrary to model predictions he got slightly faster along the delay conditions.

From the mean RT data it is clear that participants DS and PB were unable to achieve the goal set for the

stop experiment of keeping up the mean RT they had exhibited in the go training. It was evident that introducing the stop trials had an effect on the go processing of these two participants, probably in the form of unconscious and unintended strategies favouring good stopping performance. This procrastination strategy is a well-established consequence of the conflict situation participants are in when trying to inhibit well-practised responses (e.g., Lappin and Eriksen 1966; Ollman 1973), and suggests a violation of the race model assumption of context-independent processing. Therefore, the data obtained from HB, who did not seem to adopt a speed-accuracy trading strategy, were of higher relevance and interest for the more detailed fitting of the RT data to the model predictions than the data from the other participants.

Plotting the stop failure RT distributions from each delay condition, along with the appropriate upper bound and the common lower bound for that participant, revealed similar violations of the race model for all the three participants. The slowest 10–15% of the stop failure responses performed in the first delay condition were unexpectedly slow and should, according to model predictions, have been inhibited by the stop process. Several earlier studies have shown these violations of race model predictions for some of the participants tested (e.g., Logan and Cowan 1984; Hanes and Carpenter 1999; Colonius et al. 2001). The fact that the violations tend to occur on trials with short SSDs, and specifically on the slowest reactions on these trials, suggests that the presentation of the stop signal affects the processing of the go signal on those trials. Özyurt et al. (2003) proposed that stop signal interference with go processing might slow down this operation, and hence also the response made on such trials. Alternatively, go signal interference with stop signal processing might delay the progress of that operation and allow for slow responses to be executed despite proper initiation of the inhibition process. In this vein, an elaborated race model, introducing mutual inhibition of the go and stop processes after a period of independence, has been suggested by Boucher et al. (2003).

Recently, visual-tactile interactions in saccade generation have also been observed in the focussed attention paradigm where the tactile stimulus plays the role of an accessory stimulus (Diederich et al. 2003). Amlôt et al. (2003) found reduced saccade latencies to a visual target when the tactile stimulus was presented before the visual stimulus, whereas Colonius and Diederich (2004) observed facilitation also in the case of a tactile stimulus following the visual target. Thus, in the countermanding task, a response to the visual target could be expedited by the occurrence of the stop signal, thereby making suppressing the go response more difficult. This hypothesis does not deny the different functional roles of the tactile stimulus in the focussed attention and the stop signal tasks. Before the tactile stimulus can be interpreted as a stop signal (requiring a cortically based decision process), it has to be detected; and at this early

stage, its function may be similar to the nontarget in the focussed attention task.

An interaction between the go and stop processes would be expected to affect not only the RTs but also the amplitudes of the stop failure saccades. The direction and amplitude of a saccade are thought to be programmed before the start of the actual movement (e.g., Findlay and Walker 1999). However, presenting an additional stimulus may affect the movement as it is carried out, even if the modality of the additional stimulus is different from the target stimulus. For example, Doyle and Walker (2002) found that a visual accessory stimulus affected the trajectory of voluntary saccades to a visual target regardless of the instruction, whereas auditory and tactile stimuli did so only when they were relevant for the task. As the appearance of the tactile stop signal was a highly informative signal in the present experiment, it would be expected that this would affect the saccadic amplitudes as well as the RTs. Colonius et al. (2001) and Özyurt et al. (2003) reported findings of hypometric saccades on stop failure trials, and interpreted these as evidence for the stop signal affecting the dynamics of the ongoing saccade, in contradiction with the context-invariance of the race model. More specifically, in their data the length of time which passed on stop failure trials between the stop signal presentation and the response was correlated with the decrease in saccadic amplitudes, compared to amplitudes on the go trials. They suggested that stop signal processing might affect saccadic processing, and that increasing concurrent go and stop processing would accumulate this effect. In both studies, the fast saccades performed by several participants had extremely reduced amplitudes, which was interpreted as strategic responding at a time when the presentation of the stop signal was likely.

The participants in this experiment produced quite accurate saccades to the go signal, which was always presented either at -10° or at 10° of the visual angle in the horizontal plane. Across participants, the mean amplitudes of the conditions ranged from 9.4° to 12.3° of visual angle, and the largest standard error was 0.6° of visual angle. It seems that it was very easy to perform an exact movement towards the red light in the otherwise dark experimental room, despite the fact that spatial accuracy was not specifically called for and no feedback was given about it during practice or the experiment. Thus, the small, but in most cases systematic and statistically significant, differences in mean saccadic amplitudes in the stop experiment were unlikely to be due to the natural variability in saccade sizes. For all participants, amplitudes in the three delay conditions were smaller than those on the go control trials, and the smallest mean amplitudes were measured in the first delay condition. Hence, earlier stop signals which failed to produce inhibition had larger effects on the size of the resulting saccade than later ones.

Both the amplitude effects on the go trials and those on the stop failure trials reported in Colonius et al.

(2001) and in Özyurt et al. (2003) were replicated in this experiment. In the go control trials, DS and HB produced much smaller saccades when the response was fast (<140 ms) than when the movement was around the mean RT or slower. At this point of the trial, a possible stop signal would already have occurred for HB, and would be increasingly unlikely for DS. Thus, the strategy of expecting a stop signal when it is most likely to appear would produce effects around this latency and before it. A state of simultaneous preparation for the possibilities of movement and inhibition might affect motor programming of the saccade so that resulting saccades are hypometric. Accordingly, the go training data of HB were very similar to that in the go control condition, but did not show hypometricity on fast reactions. The go training data from DS featured generally small movements, but without the distinct dip in size on the fast reactions.

Further, it is not immediately clear how the possible simultaneous preparation would have produced the similarly hypometric saccades in the first bin of the stop failures, as produced by both DS and HB and also present in the data obtained by Colonius and colleagues. As these responses involved only up to about 50 ms concurrent go and stop processing, and the latest possible stop signal was presented 170 ms (DS) or 110 ms after the go signal, the first bin cannot include slow responses. Instead, the fastest stop failures are likely to be found in this bin, possibly including express saccades. These are extremely fast (around 100 ms in humans), tend to have smaller amplitudes than regular saccades (e.g., Fischer and Weber 1993), and are most frequent when the stimulus presentation involves a gap between the fixation point and the imperative stimulus, as was the case in this experiment. Thus, the possibility of a substantial proportion of express saccades in the first bin might explain the hypometricity found in the data from DS and HB in both the go control and stop failure conditions, as well as in the go training for DS.

The patterns seen in the amplitude data suggest the possibility of an effect of the stop signal on the programming or execution of the saccade. However, the present data are by no means conclusive, particularly considering the sizes of the effects in relation to the accuracy of the infrared light video system used. Future experiments using more than one go signal position on each side, including stimuli at larger visual angles, are needed to clarify this issue.

Finally, the estimated SSPTs showed that the participants were good at cancelling their eye movements when suddenly required to do so. The differences in the inhibitory performance between participants were relatively small. HB, who required shorter SSDs than the other two participants to achieve similar levels of inhibition success, consequently had the longest SSPT. Note that these estimated SSPTs are shorter than those frequently reported in the stop signal literature covering countermanding of manual movements (e.g., Logan 1994; Williams et al. 1999). Even shorter SSPTs have,

however, been obtained using visual go and auditory stop signals (Colonius et al. 2001; Özyurt et al. 2003). Thus the intermediate peripheral processing time of tactile stimuli, relative to visual and auditory stimuli (e.g., Todd 1912; Diederich 1995; Colonius and Diederich 2004; Diederich and Colonius 2004), would support rather shorter SSPTs than those obtained in the majority of stop experiments using only visual stimulation. Further, SSPTs have been shown to be shorter for saccadic responses, similarly to the generally shorter latencies for saccades compared to manual responses (Logan and Irwin 2000). Thus, the estimated SSPTs also mirror the comparatively short RTs obtained in the present experiment.

Conclusion

The experiment showed, for the first time, that a tactile stimulus can be employed successfully as a stop signal in a saccadic RT task with visual go signals. Each of the three participants exhibited deteriorating stopping performance with increasing delay of the vibratory stop signal relative to the imperative visual go signal. The estimated SSPTs were shorter than those found in the literature with manual responses. The comparisons of mean saccadic RTs across conditions showed that introduction of stop trials affected the go performance of two of the participants to the extent that they slowed their responding significantly in expectation of the stop signal. Although the data were in general agreement with the predictions of the Logan–Cowan race model, all participants were slower than expected on a proportion of responses in the shortest delay condition. These small but consistent violations of predictions, along with the hypometric saccades on stop failure trials exhibited by all participants and reaching statistical significance for two of them, support suggestions of earlier studies that the race model needs some elaboration to account for such data.

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