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Individual stopping times and cognitive control: Converging evidence for the stop signal task from a continuous tracking paradigm

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The present study introduces a continuous tracking procedure to investigate cognitive stopping in individual trials. Our measure of stopping performance had a mean similar to mean stopping times estimated in the stop signal paradigm, suggesting a common underlying process. Additional findings indicate that stopping performance and tracking performance were dissociable. First, while stopping times were primarily affected by stop signal modality, tracking performance was primarily affected by tracking difficulty. Second, tracking performance influenced tracking but not stopping in immediately following trials. Stopping influenced neither tracking performance nor stopping in immediately following trials. Finally, there was no correlation between tracking performance and stopping performance, or any dependency between them as found in the conditional means.

The control of our actions is an important aspect of human behaviour. An extreme form of cognitive control is stopping an overt action. For example, upon the conductor's signal the musicians must abruptly cease playing their instruments. The cognitive aspects of stopping have been primarily investigated within the framework of the stop signal or countermanding procedure (Logan, 1994; Logan & Cowan, 1984; Osman, Kornblum, & Meyer, 1986, 1990). This procedure employs a choice or a simple reaction time (RT) task (the go task), and in certain trials the participants receive an additional signal (the stop signal) indicating that they must refrain from carrying out the intended response. By varying the delay between the go and stop signals, an inhibition function can be calculated, presenting the probability of response inhibition as a function of the delay or some transformation of it (Logan, 1981, 1982; Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984).

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The stop signal procedure has been developed hand in hand with its theoretical framework, the race model, which assumes that the go and stop processes race in parallel, independent of each other. Together, the model and experimental procedure enable calculation of the time required for completion of the inhibition of the action. This time is commonly referred to as the SSRT (stop signal reaction time). SSRT cannot be computed directly from behavioural data, but its estimate is derived mathematically employing one or more assumptions. Of these, the most essential is the stochastic independence of go and stop processes. Thus, the finishing times of the go process are independent of the finishing times of the stop process (Logan, 1994). Much research in the area has focused upon validating the race model and examining the influence of various manipulations on ballistic, automatic, and controlled processes (De Jong, Coles, Logan, & Gratton, 1990; Logan, 1982; Osman et al., 1986, 1990). Aside from its importance for the calculation of SSRT, the independence of stop and go processes has broader theoretical relevance, since several authors have suggested that control processes (such as stopping) and controlled processes (such as going) are dissociable (e.g., Gopher, Armony, & Greenshpan, 2000).

In spite of its elegance, the stop signal paradigm provides only a single statistical measurement of SSRT and does not enable measuring individual stopping times. Colonius (1990) proposed a means of calculating the entire inhibition distribution, but nonetheless the method provides an estimate and is based on several assumptions. In this study we present a procedure analogous to the stop signal paradigm, where the stopping is observable as an overt action. This task enables us to determine individual stopping times by measuring stopping in a continuous go task. To investigate the stopping times estimated on the basis of the new procedure, we capitalized on several relatively well-established findings concerning the stop signal paradigm. Specifically, research using the stop signal procedure has determined that SSRT is relatively stable across conditions, participants, and tasks (Jennings, van der Molen, Brock, & Somsen, 1992; Logan, 1994). SSRT was also found to be little affected (Logan & Burkell, 1986), or totally unchanged (Logan et al., 1984) by practice. Thus, most research utilizing the stop signal procedure points to a unitary mechanism of stopping (Band & van Boxtel, 1999), invariant across different requirements and situations, and even assumes it (Osman et al., 1986, 1990). In accordance with this conclusion, mean SSRT is consistently found to be between 200 and 400 ms (Logan, 1994).

It should be noted that De Jong, Coles, and Logan (1995) proposed an alternative view according to which there are two mechanisms of inhibition: a central mechanism that is relatively slow, controlled, and selective, and a peripheral mechanism that is relatively fast but nonselective. Thus, this model suggests that inhibitory processes vary in different situations and could involve distinct strategies. De Jong et al. also questioned the validity of the key assumption of the race model: the independence of stop and go processes. Consequently, it is unclear at present what mechanisms of inhibition exist and their relations to other cognitive processes.

As mentioned earlier, the current procedure measures stopping a continuous response. Using such a task is consistent with previous research on stopping. For example, Logan and Cowan (1984) and Logan (1994) suggested that the inhibition of continuous responses is similar to that of discrete responses. Ladefoged, Silverstein, and Papcun (1973) examined the interruptibility of speech, considered to be a continuous response. They monitored speech responses after participants were given a signal to stop and initiate a different response (e.g., tapping). Although Ladefoged et al. arrived at individual stopping times, their main interest was the differences in the ability to stop during different stages of speech. Continuous tasks have also been used within the framework of the stop signal procedure. De Jong et al. (1990, 1995) used a continuous response but applied a discrete criterion to it in order to employ the race model and the mathematical procedure to estimate SSRT.

In the following experiments we asked participants to track a visual stimulus with the aid of a computer mouse. This made it possible to continuously and directly measure the process of stopping when participants were given a signal to stop without relying on a specific model and its various assumptions. Another advantage of using a continuous go task is that it enables one to arrive at the SSRT for each individual trial, as opposed to a mean SSRT derived from the race model. Individual measures for each trial allow several fine grain analyses of the results, which could lead to novel insights regarding stopping behaviour.

One reason why individual stopping times may be interesting is the recent developments in RT research. These show that some important attentional processes have a selective influence on the upper tail of the RT distribution (e.g., Jolicoeur & Dell'Acqua, 1998; Spieler, 2001). Such differential effects can be seen by looking at how a given manipulation affects the various quintiles of the distribution, a procedure known as Vincentizing (e.g., De Jong, Berendsen, & Cools, 1999). In addition, individual stopping times make it possible to examine sequential effects, such as how performance on the previous trial influenced performance on the current trial. Previously, Rieger and Gauggel (1999) found that RTs to the go task were delayed when following stop signal trials. Nonetheless in the conventional stop signal task, sequential effects on the inhibition process cannot be observed and to date have not been estimated. In the present task, we were able to compute across-trial correlations between tracking (go) and stopping performance measures and to study trial-to-trial sequential effects for both measures.

Our main interest was in exploring the continuous tracking task and validating it. Moreover, this study was designed to provide an initial demonstration of the advantages of the tracking task. Since the go task was continuous, we were able to measure overt stopping performance and detect the time and distance where the first signs of stopping were evident in each trial. The present task allows one to take advantage of the individual SSRTs to examine in depth, and relatively directly, the issue of independence of stop and go processes. The procedure should provide information from a different route of inquiry from those used before. It must be noted that the operational definition of the SSRT in the current procedure does differ from that defined by the stop signal procedure, although our estimates were surprisingly similar.

EXPERIMENT 1

In order to validate the tracking procedure, several manipulations were included in the first experiment. It has been demonstrated that auditory RTs are faster than visual RTs, although the reasons for this phenomenon are disputed (Goldstone, 1968; Kohfeld, 1971; Woodworth & Schlosberg, 1954). Given the simple RT-like aspects of stopping performance (Logan & Cowan, 1984), one would predict faster stopping times in response to auditory stop signals than in response to visual stop signals. This would be in accordance with Colonius, Ozyurt, and Arndt (2001) who have found this to be the case for inhibition of eye movements. In addition, tracking difficulty (manipulated through target speed) was expected to affect tracking performance but not stopping performance. Tracking performance was estimated by *tracking distance*, the distance between the target and the mouse cursor, with a smaller distance indicating better performance. It was postulated that signal modality would influence stopping processes (mainly SSRT) while tracking difficulty would influence task execution processes (mainly tracking distance). Finally, trial length was manipulated as an exploratory variable, to examine whether expectancies and top down mechanisms may influence performance (Logan, 1994). Trial length was defined as the time from the onset of the trial to the onset of the stop signal. Note that trial length could be seen as analogous to the frequency of stop signal trials in the stop signal paradigm. The longer the trial length, the less frequent the stop signals in a given period of time.

Method

Participants

We present results from 12 undergraduate students at Ben-Gurion University of the Negev, who participated in the experiment as part of the requirements for an introductory psychology course. All participants (7 women and 5 men) reported being right handed and having normal or corrected-to-normal vision and hearing. One participant failed to stop on a high percentage of the trials (due to self-reported fatigue) and was replaced by another.

Apparatus and stimuli

The tracking task was performed on an IBM-compatible Pentium 200-MHz computer with RAM memory of 64k, a 14" colour monitor (screen resolution 480 by 640 pixels), and a standard mouse (Logitech PS2). Since the computer program demanded high performance, these were the minimal requirements necessary to run the experiment. Participants were seated approximately 50 cm from the screen and were given an optional mouse pad to use at their own convenience.

The visual stimuli in the experiment consisted of a target: a green square (0.69° by 0.69°, measured in visual angles) and the standard white mouse cursor arrow (0.57° by 0.80°) presented on a black background. The visual stop signal was the flashing of the entire screen in red for 100 ms, while the auditory stop signal was a 100 ms tone of 1000-Hz emitted from the internal computer speaker.

Design and procedure

The independent variables (all manipulated within participants) were stop signal modality (visual, auditory), tracking difficulty (manipulated through target speed: easy, hard), and trial length (short, long).

Two parameters specified target motion. The first was the distance travelled along a trajectory; in this experiment this parameter was held constant at 180 pixels. The second parameter was the time the target was displayed on screen for a given location along the trajectory. By changing the second parameter, we manipulated target speed and, therefore, difficulty: Target display time was 65 ms for the slower/easy condition and 45 ms for the faster/difficult condition. The remaining factor, trial length, included short trials randomly selected from the range of 10–30 s (average of 20 s) and long trials randomly selected from the range of 50–70 s (average of 60 s).

The experiment comprised four sessions, of approximately 40 min each, held on consecutive days. Each session included four blocks of 11 trials. The first trial of each block was regarded as practice and was omitted from the analyses. Thus, each participant completed 160 trials that were analysed. Each block consisted of only one type of stop signal (visual/auditory) and one level of difficulty (easy/hard). Half of the trials in a block were long, and half were short, randomly presented, with the warm-up trial always being short. The order of the blocks was counterbalanced in a Latin square (per session) within an additional Latin square (per whole experiment), resulting in four possible orders.

The participants were tested individually and were read instructions briefly describing the task. The importance of the stopping task and persistence in the tracking task were emphasized equally. Each trial began with the target presented at the centre of the screen (see Figure 1 for the sequence of events in a trial). To initiate a trial, participants pressed the left button of the mouse. Upon doing so, the target began to move in a random direction as determined by the computer program. The participants tracked the target with the arrow (i.e., the mouse cursor), attempting to minimize the distance between them. It was pointed out in the instructions that keeping the cursor on the target is extremely difficult and that merely keeping it as close as possible would be sufficient. At the end of each trajectory, the target began another with the direction determined randomly by the program until the time determined by trial length, after which the stop signal was presented. The participants persisted in the tracking task until given the stop signal and then they stopped as fast as possible. They were told that in order for the stop to be considered, they had to refrain from moving the cursor for several seconds without lifting their hand (the program considered a 1-s pause of the mouse as a final stop). After an interval of 4 s after the mouse cursor was stopped completely, the next trial began with the target in the centre of the screen. If the participant did not stop the mouse from moving within 10 s of receiving the stop signal, the next trial began.

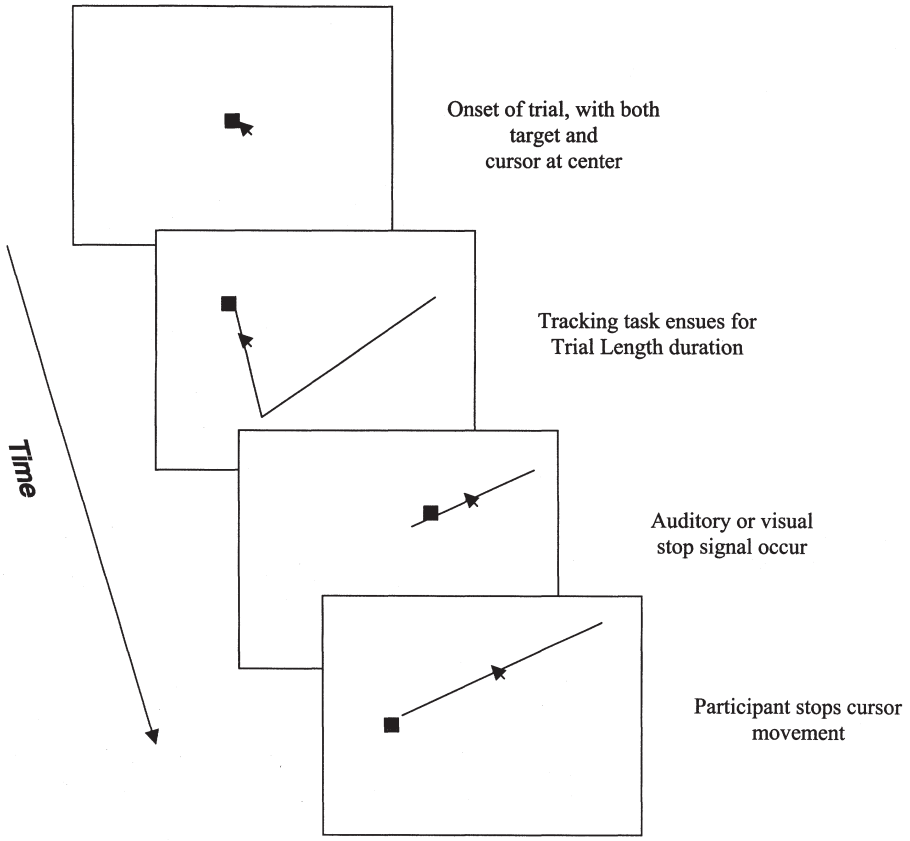

Figure 1. A schematic representation of the main sequence of events that occur on each trial.

Results and discussion

Data collection and computation

For each trial, many different samples of data were collected both before and after the stop signal, yielding different dependent measures. One measure, *tracking distance*, was the mean Euclidean tracking distance (in pixels) between the mouse cursor and the target during the last 5 s before the stop signal. Small tracking distance indicates better performance. Each tracking distance value was the average of at least 147 samples taken by the program during the 5 s.

The remainder of the data were collected after the presentation of the stop signal. From the onset of the stop signal, the program noted the two-dimensional spatial coordinates of the mouse cursor on the computer screen. The program then computed the average Euclidean distance between the present cursor position and the cursor position at which the stop signal was initiated. The average Euclidean distance was based on a sampling of the spatial coordinates during the 20-ms interval.

Final stopping time was defined as the time between the onset of the stop signal and final stopping. *Final stopping distance* consisted of the Euclidean distance (in pixels) between the initial cursor position (at the time of the stop signal) and the cursor position at the time of the final stop. SSRT was defined as the time, computed by an analysis program, when the initial signs of stopping could be observed in the continuous tracking performance (the detailed algorithm is described below). SSDIS (stop signal distance) is the distance between the position of the cursor at the time of the stop signal and its position at the time of SSRT. All dependent variables, aside from the tracking distance, are portrayed graphically in Figure 2.

On initial examination of the continuous difference performance, it was noted that a consistent pattern emerged when plotting distance as a function of time elapsed since the onset of the stop signal (see Figure 2). At first, the function was linear, portraying movement at a constant speed. Then the function decelerated, indicating that the participant began stopping.[1]

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[1] A possible objection to this procedure is that the participants simply continued tracking, and the observed pattern of deceleration simply reflected a change in cursor trajectory. There are several reasons why this is implausible. First, when we observed the participants, we saw that they stopped almost immediately with no obvious changes in trajectory. Second, tracking difficulty (manipulated by target speed) did not significantly affect SSRT, while SSRT was influenced by stop signal modality. Tracking difficulty was strongly related to changes in target trajectory since the distance along a given trajectory was constant, 180 pixels. Since the stop signal was given randomly, independently of the position along the trajectory, the chances that the trajectory would change during stopping were higher when tracking was more difficult, and the target moved faster. Third, there was a high correlation, .82, between SSDIS and final stopping, which strongly suggests that SSDIS reflected stopping. Fourth, if initial stopping reflected only a change in trajectory, the average SSDIS should have been 90 pixels (one half of trajectory length), but in practice it was much shorter, 39.90. Fifth, the ratio of target speeds between hard tracking and easy tracking was $65/45 = 1.44$, whereas the ratio of tracking speeds after the stop signal and until initial stopping was 0.23 pixels/ms vs. 14 pixels/ms, a ratio of 1.64 (this difference between tracking speeds was the only significant effect in the analysis of variance (ANOVA), $F(1, 11) = 133.12$, $MSE = 2.63$, $p < .001$). In other words, the ratio of tracking speeds was numerically larger than the ratio of target speeds. However, if stopping merely reflected a trajectory change, one would expect the reverse pattern. Specifically, we measured the Euclidean distance from the stopping point, whereas the actual distance presumably travelled was city-block—that is, larger. Hence, the speed we observed when a trajectory change occurred was smaller than the actual speed. Moreover, a trajectory change was more likely when tracking was difficult. Hence, the expected tracking speed ratios, according to the argument, would be lower than the target speed ratios, whereas in practice we observed the reverse pattern.

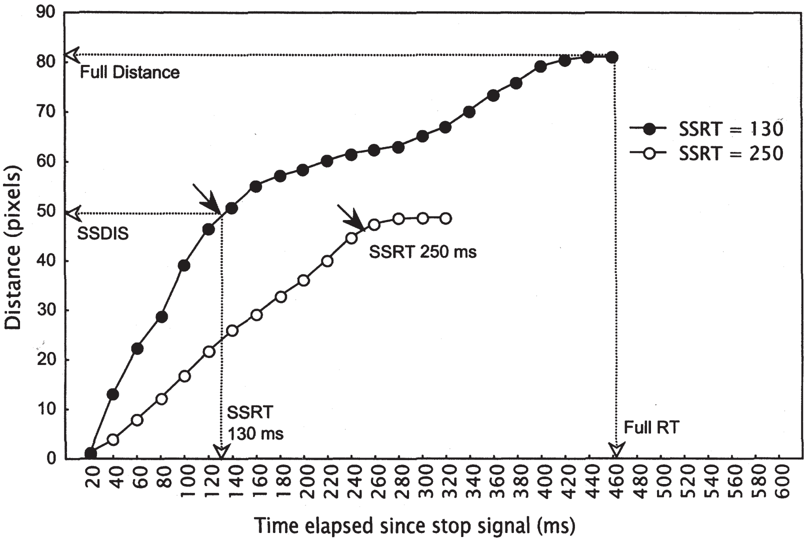

Figure 2. A plot of the distance as a function of time, for exemplar trials with SSRT of 130 ms and 250 ms. Horizontal and vertical dashed lines illustrate four of the dependent variables for the trial where SSRT is 250 ms. Full arrowheads indicate the point in time where the initial signs of stopping are identified by the algorithm. Empty arrowheads indicate the values of each of the dependent measures.

Consequently, we used the following algorithm to detect the point at which substantial deceleration occurred (i.e., when the function stopped being linear). A linear regression analysis was performed initially on the first five measurements (equivalent to the first 100 ms), with distance from the stop signal point as the dependent variable and time bin as the independent variable. The resulting regression model was used to predict the distance of Measurement 6. In the next iteration, the regression analysis included Measurements 1–6, to predict the distance of Measurement 7, and so forth until the 104th observation. Stopping initiation was defined as the point after which four consecutive positive deviations were identified (i.e., where the predicted cursor distance was larger than the actual cursor distance). Four consecutive positive deviations were selected as the criterion, because the probability of this occurring by chance is $1/2^4$ or 0.0625, close to conventional significance levels.

Because the regression began with the first five observations, the minimal stopping initiation could be detected in the sixth observation. The algorithm then averaged the time of the *n* trial with that of the *n* + 1 trial, in order to produce a conservative measurement, since slowing began somewhere between the two measurements. Therefore the range of SSRT was predetermined to be between 130 ms and 2030 ms, with a temporal resolution of 20 ms. For example, if from the sixth measurement, the deviations continued to increase, the resulting SSRT would be computed as follows: 6*20 + 10, yielding a SSRT of 130 ms. The algorithm successfully detected stopping in 78% of the trials. In the remainder of the trials the algorithm did not detect the commencing of a stop according to the prespecified criterion, and these were labelled as trials in which SSRT was undetermined. In the example trials in Figure 1 the algorithm identified the initial stopping (SSRT) at 130 ms and 250 ms.

Overview of analyses on tracking distance, final stopping time/distance and SSRT/DIS

The analyses comprised two parts. First, analyses of means were conducted and, following that, analyses of individual trials. The second part can only be performed when there are measures of individual stopping times. Figure 3 presents a schematic outline describing the analyses performed and the main results.

Analyses of means

Trials where final stopping time was fastest (1.2%, less than 100 ms) or slowest (1.2%, over 3000 ms) were discarded from all analyses.

Analyses of all trials. As predicted, tracking distance was shorter for easy trials than for difficult trials. In other words, participants managed to get the cursor closer to the target when the tracking was easy than when it was difficult. Furthermore, auditory final stopping time was shorter than visual final stopping time. Moreover, final stopping distance was longer when tracking was difficult than when it was easy. The fact that final stopping distance but not final stopping time was affected by tracking difficulty is easily explained by the fact that target (and tracking) speed was higher when tracking was difficult than when tracking was easy. Thus, given similar times, more distance was travelled when breaking in the difficult condition.

Analyses of variance (ANOVAs) performed on tracking distance, final stopping time, and final stopping distance according to the variables described in Design and Procedure confirmed these results. There was a significant effect of tracking difficulty on tracking distance, $F(1, 11) = 132.1$, $p < .001$. Average tracking distance was 26.6 pixels when tracking was easy and 38.76 pixels when tracking was difficult. No other sources of variance were significant in this analysis. An ANOVA on final stopping time revealed only a main effect of stop signal modality, $F(1, 11) = 4.58$, $p < .05$, where the average final stopping time was 494 ms for the visual signal and 450 ms for the auditory signal. An ANOVA on final stopping distance indicated only an effect of tracking difficulty, $F(1, 11) = 54.4$, $p < .001$, where the average final stopping distance was 39 pixels for the easier tracking condition and 57 pixels for the more difficult condition.

Analyses of determined SSRT trials. The algorithm successfully detected initial stopping in most of the trials (78%), and in these trials we could compute SSRT and SSDIS. As predicted, auditory SSRT was shorter (230 ms) than visual SSRT (240 ms). In addition, SSDIS was shorter when tracking was easy (31 pixels) than when it was difficult (48 pixels). An ANOVA on SSRT revealed a significant main effect for stop signal modality, $F(1, 11) = 13.00$, $p < .01$. The ANOVA on SSDIS indicated an effect of tracking difficulty, $F(1, 11) = 145.3$, $p < .001$.

Although SSRT and SSDIS appear to be superior measures with less noise due to motor activity, the present analyses were not conducted on the same sample as that in the previous analysis. To ensure comparability of the two samples, we repeated the analyses of final stopping time/distance on trials with determined SSRT. The results were analogous to those found when all trials were analysed. An ANOVA on final stopping time data revealed the effect of signal modality, $F(1, 11) = 6.05$, $p < .05$, with means of 541 ms and 487 ms for the visual and auditory signal, respectively. Analysis of final stopping distance indicated the effect of level of difficulty, $F(1, 11) = 72.66$, $p < .001$, with means of 41 and 60 pixels on average for the slower and faster conditions respectively.[2]

Analyses of trials with undetermined SSRT. Since SSRT/DIS were undetermined for 22% of the trials, analyses of these trials could only apply to final stopping time and final stopping distance. Nonetheless, we sought to further ensure the generality of our conclusions. The ANOVA on final stopping time did not reveal any significant effects, although signal modality did reach a significance level of $p < .09$ in the same direction as that in the previous analyses. The ANOVA on final stopping distance revealed a main effect of tracking difficulty, $F(1, 11) = 6.65$, $p < .05$. Mean final stopping distance was shorter (31 pixels) when tracking was easy than when it was difficult (42 pixels). Unlike in the previous analyses, there was also a significant effect of trial length, $F(1, 11) = 6.13$, $p < .05$. Mean final stopping distance on shorter trials was 39 pixels, and for longer trials 33 pixels. Thus, the results are similar though not identical to those of the previous analyses. The differences could be attributed to the much smaller number of trials on which these analyses were based.

Comparison of determined and undetermined SSRT trials. The present analyses constitute an attempt to clarify the differences between trials with determined SSRT and without determined SSRT. The only difference, which we identified, was that when SSRT was determined, stopping was delayed both in time and in distance (see Appendix for additional analyses).

Mean final stopping time was shorter (321 ms) in undetermined SSRT trials than in determined SSRT trials (514 ms), $t(1875) = 10.76$, $SE = 18.05$, $p < .01$. Likewise, mean final stopping distance was shorter (36 pixels) in undetermined SSRT trials than in determined SSRT trials (51 pixels), $t(1875) = -5.92$, $SE = 2.52$, $p < .01$.

In order to examine the average frequency of each trial type at each stage of the experiment, two additional tests were performed. These analyses indicated that undetermined SSRT trials were equally common at various stages of the experiment and were not more common under any particular condition. The first analysis compared the average sequential trial number across sessions of each trial type, $t(1875) = 0.96$, *ns*. The second compared the average number of each trial type, within session, collapsed across all four sessions, $t(1875) = 0.3$, *ns*. In addition, a series of χ^2 tests examined whether the relative frequencies of determined and undetermined SSRT trials were related to the three independent variables. All the tests were nonsignificant, all $\chi^2(1) < 1.8$.

Analyses of individual trials

Overview of analyses of individual trials. In the following analyses, we realized the advantages of measuring individual stopping times. These consisted of comparisons of distributions, Pearson correlations, and sequential effects (see Figure 3).

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[2] We also analysed two difference measures: RT Diff = final stopping time – SSRT, and DIS Diff = final stopping distance – SSDIS. These analyses were repeated whenever applicable and no significant effects were found.

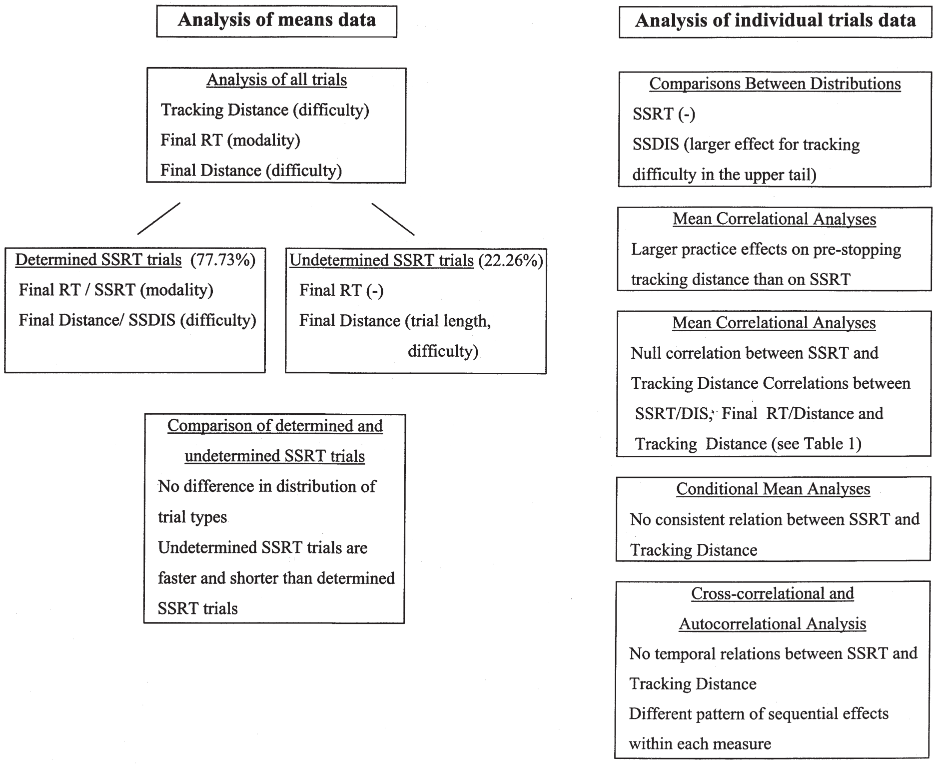

Figure 3. Main analyses and results in Experiment 1. In each analysis box the dependent measures yielding significant results are shown with the significant factors in parentheses.

Distribution comparisons. It is possible that although the means were not influenced by some manipulations, the shape of the distributions may have been affected. The results suggest that this is not the case. Vincentizing of SSRT (e.g., Ratcliff, 1979) indicated that all the effects reported above were statistically equivalent across the different parts of the distribution, when the 5th, 25th, 50th, 75th, and 95th percentiles were examined. Thus, an ANOVA that included percentile as an additional factor did not show any additional effects other than a trivial main effect for percentile, $F(4, 44) = 183.9, p < .001$. Vincintizing SSDIS indicated that SSDIS was longer for harder trials, as found before, but interestingly this effect was larger in the upper tail of the distribution than in the lower tail of the distribution. This was verified in an ANOVA that included percentile as a factor. There were main effects for percentile, $F(4, 44) = 136.8, p < .001$, and tracking difficulty, $F(4, 44) = 76.1, p < .001$, as well as an interaction between them, $F(4, 44) = 18.2, p < .001$. This interaction reflected the fact that the effect of tracking difficulty was larger among trials where SSDIS was relatively large (for the 75th and 95th percentiles) than among those were SSDIS was relatively short (the lower percentiles), $F(1, 11) = 25.7, p < .01$.

Pearson correlations. Correlational analyses were used for two major purposes: first, to examine practice effects; and second, to explore the intercorrelations between the various

TABLE 1
Mean correlations between main dependent variables for Experiments 1 and 2

	SSRT	*SSDIS*	*Final stopping time*	*Final stopping distance*	*Tracking distance*
SSRT	—	.17*	.17*	–.01	–.02
SSDIS	.39*	—	.01	.82*	.25*
Final stopping time	.29*	.13*	—	.09*	.03
Final stopping distance	.28*	.94*	.14*	—	.29*
Tracking distance	.03	.26*	.01	.24*	—

Note: Correlations for Experiment 1 are above the diagonal, and correlations for Experiment 2 are below the diagonal. Mean correlations and combined significance computed using Fisher's Zr transformation and Rosenthal's (1991) procedure. All times are in milliseconds, and all distances are in pixels. SSRT = stop signal reaction time; SSDIS = stop signal distance; final stopping time = final reaction time.

* $p < .05$.

dependent measures, most notably between tracking distance and SSRT. The most important result is the practically null correlation between tracking distance (indicating the efficiency of "go" processes) and SSRT (indicating stopping efficiency). Moreover, practice effects on SSRT were negligible. Analyses in this section were performed using meta-analytic procedures specified by Rosenthal (1991). Initially, correlations on individual trials were calculated within each participant separately, and then the Fisher's Z transformations of the correlations were averaged across participants. In addition, the combined significance using Rosenthal's combined Z test was computed.

Practice effects on SSRT were explored by computing the mean correlation between SSRT and sequential trial number, which was $r = -.05$, and significant, $Z = 2.03$, $p < .05$. Although practice resulted in significantly shorter SSRT, as there was a negative correlation between trial number and SSRT, the effect was negligible in size. A somewhat larger effect of practice was found for tracking distance, where the mean correlation between tracking distance and sequential trial number was $r = -.12$, and significant, $Z = -5.05$, $p < .001$. The means of Pearson correlations between each two of the dependent variables were examined in the same manner. These values appear above the principal diagonal in Table 1 (each value represents a mean of 12 correlations). The most important finding is that of a practically null correlation between SSRT and tracking distance. In addition, there were significant correlations among the two stopping time measures (SSRT and final stopping time), and among the two stopping distance measures (SSDIS and final stopping distance).

Sequential effects. In this section, we explored how performance in previous trials affected performance in the current trial. The results indicated that tracking distance in previous trials affected tracking distance but not SSRT in the current trial. Furthermore, SSRT in previous trials affected neither SSRT in the current trial, nor tracking distance.

Tracking distance was taken to be the best estimate of tracking performance, while SSRT was taken to be the best estimate of stopping performance. As seen in Table 1, the correlation between them was extremely low and nonsignificant. In order to examine the relation between these measures in detail, cross-correlation analysis (i.e., the correlation between SSRT in preceding trials and tracking distance in the current trial or vice versa) was performed between them for lags of 0 to 24. In addition, we explored the possibility of sequential relations within each of these two measures by computing autocorrelations with lags of 0 to 24 (i.e., the correlation between SSRT in preceding trials and SSRT in the current trial and the same for tracking distance). The analyses were performed separately for each participant. The results of the cross-correlation analysis indicated no consistent pattern, supporting the initial conclusion that there is no correspondence between the tracking distance and the SSRT.

The autocorrelation analyses performed individually for tracking distance and SSRT revealed very different patterns. Maximal positive autocorrelations for tracking distance were at a lag of 1 or 2 for 10 of the 12 participants (mean lag for maximal autocorrelation was 3.1). The maximal positive autocorrelations for SSRT were on average at a lag of 9.25. The range of maximal autocorrelations for tracking distance was between $r = -.21$ and $r = .45$, and for SSRT between $r = -.15$ and $r = .26$. Thus, while tracking distance had the highest positive autocorrelations at shorter lags, SSRT had no such systematic ordering of autocorrelations. This finding indicated that performance on a given trial was influenced by preceding trials in the case of tracking performance, but not in the case of stopping performance.

Conditional means. While Pearson correlation measures the linear relation between two variables, in order to test stochastic independence one needs to consider other forms of relation as well (Poldrack, 1996). We therefore computed the eta-square of SSRT conditioned on the binned tracking distance (10 equal bins) and the eta-square of tracking distance conditioned on the binned SSRT. These analyses examine whether SSRT could be predicted from tracking distance and vice versa. If the finishing times of each process are indeed independent one from the other then the conditional means will not show any consistent pattern of results. Specifically, for each participant we binned one measure, computed the conditional means of the other, and compared these means using an ANOVA. When these analyses were performed, there was only 1 significant eta-square out of a possible 12 in predicting SSRT from tracking distance. Moreover, there were no significant eta-squares in predicting tracking distance from SSRT. The significant result was due to the first bin being significantly longer than all the others. Eta-square values ranged from .047 to .144 for SSRT when binning tracking distance, and .037 to .111 for tracking distance when binning SSRT. In addition, we aggregated the data across all participants. This enables us to look for commonalities, and it increased the statistical power substantially. The results indicated nonsignificant eta-squares in both analyses.

Conclusions

In conclusion the results indicated that SSRT and final stopping time were affected by the stop signal modality, while tracking distance, SSDIS, and final stopping distance were affected by tracking difficulty. The analyses of the individual trials indicated that signal modality did not affect the shape of the distribution of SSRT, but that tracking difficulty led to a larger effect on SSDIS in the longer responses. Pearson correlations and sequential effects indicated consistent differences between SSRT and tracking distance. Finally, conditional means also did not show any consistent relation between SSRT and tracking distance.

EXPERIMENT 2

In Experiment 1, trial length was not found to have any effect on either tracking or stopping performance. It was hypothesized that this factor might influence the expectancies of the participants regarding the likelihood of a stop signal, thus reflecting a top-down component. Since trial length was manipulated within block trials, which means it varied unpredictably between trials, it is possible that participants did not develop lasting strategies to deal with this variable. The second experiment was conducted to examine whether participants would develop stable expectancies if they received similar trial lengths within a series of trials. It was similar to Experiment 1, with the exception that trial length was either short or long within each block of trials. Furthermore, we hoped to replicate the findings of Experiment 1.

Method

Participants

A total of 12 undergraduates participated as part of the requirements for an introductory psychology course. All participants (10 women and 2 men) reported being right handed and having normal or corrected-to-normal vision and hearing.

Apparatus and stimuli

All apparatus and stimuli were identical to those of the previous experiment.

Design and procedure

The design and procedure were the same as those in Experiment 1. The only difference was that the two trial lengths were now presented in separate blocks. Since each block still included the same number of trials, blocks of short trials lasted much less than blocks of long trials. Each session included two blocks of each kind of trial length, with the order counterbalanced within session and across participants.

Results and discussion

The results were analysed in the same manner as in Experiment 1.

Analyses of means

Trials where final stopping time was faster than 100 ms and slower than 3000 ms (3.6%) were discarded from all analyses. SSRT and SSDIS were computed according to the algorithm described in Experiment 1. The algorithm detected initial stopping in 67% of the trials. Figure 4 presents a summary of the main analyses and results of Experiment 2.

Analyses of all trials. Average tracking distance was 18.1 pixels when tracking was easy and 27.1 pixels when difficult. The difference between the two levels was the same as that found in Experiment 1, although overall performance was somewhat improved. Examination of final stopping times indicated that short trials resulted in faster final stopping times. Final stopping distance was found to be shorter when tracking was difficult. Furthermore, final stopping distance was shorter for auditory signals than for visual signals when tracking was difficult.

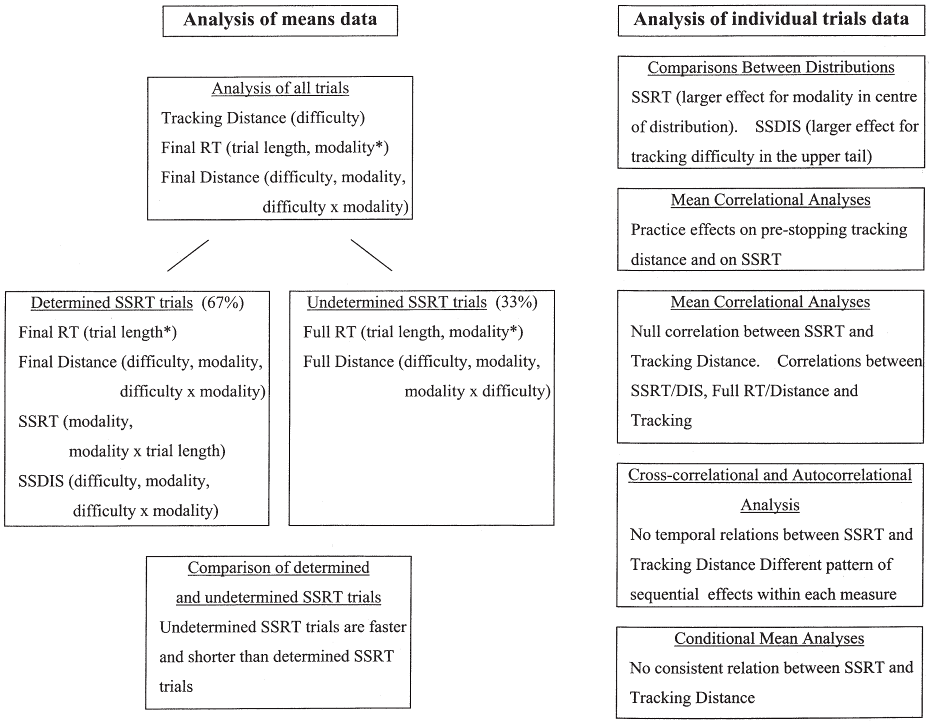

Figure 4. Main analyses and results in Experiment 2. In each analysis box the dependent measures yielding significant results are shown with the significant factors in parentheses.
Note: *Effects were marginal: $.05 < p < .1$.

An ANOVA on tracking distance with signal modality, tracking difficulty, and trial length as repeated measures found a significant effect only for tracking difficulty, $F(1, 11) = 292.7$, $p < .001$. An ANOVA on final stopping times revealed a significant effect of trial length, $F(1, 11) = 10.9$, $p < .01$. No other effects were significant, although signal modality was marginal ($p < .08$). Final stopping times were 451 ms on short trials and 486 ms on long trials. An ANOVA on final stopping distance indicated significant effects for tracking difficulty, $F(1, 11) = -150.6$, $p < .01$, signal modality, $F(1, 11) = 26.4$, $p < .01$, and their interaction, $F(1, 11) = 9.8$, $p < .01$. Mean final stopping distance was 51 pixels when tracking was difficult and 30 pixels when tracking was easy. Final stopping distance was also longer when the signal was visual (45 pixels) versus auditory (36 pixels). The interaction indicated that signal modality influenced final stopping distance when tracking was difficult (58 vs. 44 pixels for visual and auditory signals respectively), $F(1, 11) = 9.83$, $p < .01$, but not when tracking was easy (31 vs. 29 pixels for visual and auditory signals, respectively, *ns*).

Analyses of determined SSRT trials. As in Experiment 1, auditory signals led to faster SSRTs (225 ms) than did visual signals (257 ms). Furthermore, there was an interaction between signal modality and trial length, where the difference between the two modalities was larger in longer trials. SSDIS was longer when tracking was difficult (49 pixels) than for easy trials (27 pixels). In addition, SSDIS was longer when the signal was visual (43 pixels) than when it was auditory (33 pixels). Finally, there was an interaction between tracking difficulty and signal modality where the difference between modalities was larger when tracking was difficult.

An ANOVA on SSRT indicated a significant effect for signal modality, $F(1, 11) = 45.9, p < .01$, and for the interaction, $F(1, 11) = 6.3, p < .05$. A closer inspection of the interaction indicated that the difference between modalities was significant both for short trials, $F(1,11) = 7.67, p < .05$, and for long trials, $F(1, 11) = 30.1, p < .001$. Signal modality had a larger effect in the longer trials than in the shorter trials due to longer SSRTs for visual signals (263 vs. 251 ms) and shorter SSRTs for auditory signals (216 vs. 234 ms). An ANOVA on SSDIS revealed significant effects for tracking difficulty, $F(1, 11) = 105.9, p < .05$, signal modality, $F(1, 11) = 48.6, p < .05$, and their interaction, $F(1, 11) = 6.3, p < .05$. Additional analyses were conducted on final stopping time/distance trials for which SSRT was determined. The results were identical for final stopping distance, while for final stopping time trial length became marginally significant ($p < .07$).

Analyses of undetermined SSRT trials. SSRT/DIS were undetermined for 33% of the trials. In order to examine the generality of our conclusions, ANOVAs were conducted on final stopping time/distance for undetermined trials. The ANOVAs replicated the original findings as conducted on all trials.

Comparison of determined and undetermined SSRT trials. As in Experiment 1, the only difference found was that in determined SSRT trials final stopping times were longer (547 ms) and extended over a larger distance (45 pixels) than undetermined trials (302 ms and 34 pixels, for final stopping time and distance, respectively). Thus, a comparison between determined and undetermined trials for final stopping time was significant, $t(1841) = -13.78, p < .001$, as was the comparison for final stopping distance, $t(1841) = -6.52, p < .001$.

Analyses of individual trials

Comparison of distributions. In order to examine whether the entire shape of the distribution of stopping performance was affected by the manipulations in Experiment 2, additional analyses were conducted on Vincentized SSRT and SSDIS. For SSRT, the effect of signal modality was found in all but the 5th and 95th percentiles. For SSDIS, tracking difficulty was found to influence all percentiles, but as in Experiment 1 it had a larger effect in the upper percentiles (75th and 95th percentiles). Furthermore, trial length was found to influence SSDIS only on trials where the distance to the initial stop was the longest (i.e., the upper tail of the distribution). Two ANOVAs verified these findings. In the first analysis, on SSRT, main effects were found for percentile, $F(4, 44) = 175.6, p < .001$, and signal modality, $F(4, 44) = 27.4, p < .001$. Moreover, there was an interaction between the two factors, $F(4, 44) = 3.13, p < .05$, which was found to result from significant differences between SSRTs for the visual and auditory signals in all but the highest and lowest percentiles. Finally, there was an interaction between signal modality and trial length, $F(1, 11) = 5.3, p < .05$, identical to that reported in the mean analysis of SSRT. In the second analysis, conducted on SSDIS, main effects were found for all factors: percentile, $F(4, 44) = 223.4, p < .001$, signal modality, $F(1, 11) =$

24.8, $p < .001$, tracking difficulty, $F(1, 11) = 148.2$, $p < .001$, and trial length, $F(1, 11) = 8.2$, $p < .05$. In addition, several interactions were found between percentile and tracking difficulty, $F(4, 44) = 15.6$, $p < .001$, percentile and trial length, $F(1, 11) = 4.9$, $p < .05$, and signal modality and tracking difficulty, $F(4, 44) = 8.9$, $p < .001$. Tracking difficulty had a significantly larger effect in the 75th and 95th percentiles, $F(1, 11) = 32.7$, $p < .01$.

Pearson correlations. Again we hoped to examine practice effects, as well as the intercorrelations between the various dependent measures. Practice effects on SSRT were larger than those found in Experiment 1, as indicated by the mean correlation between trial position and SSRT of –.14, $Z = -17.1$, $p < .001$. The correlation between tracking and trial position was –.09 and significant, $Z = -10.1$, $p < .001$. Final stopping time/distance and SSDIS also showed correlations with trial position of the same magnitude as the correlation between SSRT and trial position. These correlations ranged from –.14 to –.11, and all were highly significant.

The mean Pearson correlations between each two of the dependent variables were also examined and are presented below the diagonal in Table 1. As in the previous experiment, there was a nonsignificant correlation between SSRT and tracking distance. In fact, all stopping measures correlated with each other, and the stopping distance measures correlated with tracking distance. Of interest is the high correlation between stopping distances measured versus the low correlation between stopping times. This replicates the finding of Experiment 1. Since further dissociations were found between the two measures, further discussion will be deferred until the next section.

Sequential effects. We examined how performance in the current trial was affected by performance in previous trials, using the analyses from the previous experiment. The cross-correlation (i.e., the correlation between SSRT in preceding trials and tracking distance in the current trial or vice versa) again did not indicate any consistent pattern, adding further evidence for the lack of correspondence between tracking performance and SSRT. The autocorrelations (the correlation between SSRT in preceding trials and SSRT in the current trial and the same for tracking distance) revealed different patterns for each of the two measures, supporting the previous finding that while preceding trials influenced tracking performance, this was not the case for stopping performance. Maximal positive autocorrelations for tracking distance were found up to lags of 3 for 10 of the 12 participants (mean lag for maximal autocorrelation was 2.5). The mean position of maximal positive autocorrelations for SSRT was 7.6. The range of maximal autocorrelations for tracking distance was between $r = -.40$ and $r = .48$, and for SSRT between $r = -.17$ and $r = .26$.

Conditional means. When SSRT was examined for each participant conditional on tracking distance bins, none of the 12 comparisons yielded significant results. Analyses of tracking distance data conditional on SSRT bins indicated that 3 comparisons of the 12 were significant. However, no consistent differences emerged; in one case the significance resulted from larger tracking distance in a fast SSRT bin, in another it was due to larger tracking distance in the slower SSRT bins, while in the third it was due to shorter tracking distance in the fastest SSRT bin. The analysis on the data aggregated across participants again showed no significant effects.

Conclusions

In summary, most of the effects found in Experiment 1 were replicated in Experiment 2. This provides converging evidence for the initial findings, suggesting that the task generates reliable results. The difference between the two experiments was the blocking of trial length in Experiment 2. Blocking trial length resulted in two related effects on stopping. First, when stop signals occurred more frequently, participants were quicker to reach a complete stop. This is an example of where strategic expectancies influence stopping performance. Second, less frequent stop signals led to a larger effect for stop signal modality. In particular, less frequent auditory stop signals led to faster stopping performance as measured by SSRT but also less frequent visual stop signals led to slower stopping performance. Consequently, when stopping was less expected the more salient auditory signal was more effective in the initiation of the stopping. The lack of convergence between final stopping time and SSRT implies that the two measures may be differentially sensitive to strategic components.

Trial length was not found to have any effect on tracking distance, indicating that tracking performance was not affected by such expectancies. This is contrary to the results typically found using the stop signal task (Logan, 1981, 1994), where expectancies have been found to influence the speed of the go task but not that of stopping performance. The present study presents evidence that the trade-off between an action and its inhibition can be shifted so as to influence the stopping process.

It can be argued that the manipulation of stop signal frequency as employed in the conventional countermanding procedure has a different influence from that of manipulating trial length in the present task. Nonetheless, in both cases expectancies are influenced by what the participant perceives to be the task that he or she is to perform most of the time. In the case of the shorter trials in the tracking task, stopping occurs more often for a given amount of time than in the longer trials.

The stopping distance measures in the current experiment were sensitive to tracking difficulty as found previously. Moreover, an effect of stop signal modality and its interaction with tracking difficulty were consistently found in all analyses of final stopping distance and SSDIS. This asserts that distance measures are sensitive to cognitive components of the stop signal such as its modality, in addition to motor components of the tracking task itself. This in turn supports the notion that the most sensitive measures of stopping performance are those based on speeded RT measures as they are not affected by motor components.

GENERAL DISCUSSION

The current experiments present a first attempt to explore a new tracking procedure to estimate individual stopping times. The results of both experiments indicated that stopping was faster to auditory stop signals than to visual stop signals. Furthermore, tracking performance was worse when tracking was more difficult, and the distances required to begin and complete the stop were longer. In Experiment 2, where trial length was consistently long or short within any given block, modality also influenced stopping distance measures in difficult trials. Furthermore, signal modality had a larger effect on longer trials for SSRT, and final stopping times were longer when trials were longer.

The continuous go task yields several direct measures of stopping performance for each individual trial. In essence, a stopping profile can be shown for each trial (for examples see Figure 2). Presently, we have shown that stopping distance measures are more sensitive to motor components such as tracking speed, while stopping RT measures are more sensitive to perceived characteristics of the stop signal itself as well as to possible cognitive aspects such as expectancies. It is also the case that measures of the final stop are not always convergent with the measures of the initial signs of stopping. This first study using the continuous tracking task has demonstrated the value of examining all of the dependent measures. In the future, one may choose only a single measure or possibly hypothesize a specific pattern of dissociations between the measures.

We capitalized on the advantages of the new procedure to examine the assumption concerning independence of stop and go processes. The results indicated that stopping performance and tracking (go) performance were dissociable. Several functional dissociations were found. First, while stopping times were primarily affected by stop signal modality, tracking performance was primarily affected by tracking difficulty. Second, in both experiments, tracking performance was affected by tracking performance in immediately preceding trials, while this was not the case for stopping performance.

Additional evidence supported the independence assumption. The correlation between tracking performance and stopping performance was close to zero and nonsignificant for both experiments. Furthermore, the conditional mean analyses indicated that there were no consistent dependencies between tracking and stopping performances. One should be careful in interpreting these analyses as supporting the independence assumption because a null correlation, for example, could result from a combination of a positive indirect link and a negative indirect link. Possibly, it could be that tracking distance is affecting negatively one meditating variable and positively another mediating variable, and both of these meditating variables have a positive correlation with SSRT, which would result in a null correlation between tracking distance and SSRT. Nonetheless, the present results add strength to the assumption of independence between stop and go processes, although they do not prove it.

One of our main goals was to show that stopping times in the new procedure are sufficiently analogous to those obtained in the stop signal paradigm. In the stop signal task all trials begin with a go signal, to which the participant is invariably required to respond. The stop signal is typically introduced before the go process has been completed. This particular task leads to a situation that can be viewed as a race in which on some occasions the go process wins the race, but on other occasions the stop process wins the race. The situation is quite different in the continuous go task where on each trial the participant both tracks the target and eventually stops. Here the go task has in a sense been "winning the race" for quite some time, and in fact the metaphor of a race reaches a limitation of sorts. When the stop signal is presented, the go process is simply deemed irrelevant, and the stopping process now takes over. There is no cause for the stop process to "lose the race", provided the participant has perceived the stop signal and is compliant with the task requirements. The typical trial length in the tracking task is currently also much longer than that of a typical trial in the stop signal procedure. In future experiments, trial length may be either extended in the conventional task, or shortened considerably in the tracking task. In addition, it may be possible to obtain a new measure of the go process by measuring RT to an unpredictable onset of target movement at the beginning of the trial. This was not possible in the current experiments as the participant initiated each trial.

Although the two tasks may be viewed as different, there are several lines of evidence that imply that they are measuring the same stopping process. First, conceptually both tasks have set out to measure the speed required to stop an overt action. Second, our findings converge surprisingly well with findings that result from research employing the stop signal procedure (Logan, 1994). The present measure of SSRT had a mean (235 ms and 241 ms for Experiments 1 and 2, respectively) similar to mean stopping times estimated in the stop signal paradigm (Logan, 1994). Estimations regarding the length of the inhibition process when using the stop signal procedure range from just below 200 up to 400 ms (Jennings et al., 1992; Logan, 1994; Logan et al., 1984; Osman et al., 1986). The mean SSRT in the present paradigm was also in this range and appeared to be stable across different samples of participants. Further support for the similarities of the two different stopping measures was found by Scheres, Oosterlaan, and Sergeant (2001) who studied children suffering from attention deficit and hyperactivity disorder (ADHD). Similarly to the stop signal paradigm, in the new procedure ADHD children had faster stopping times when methylphenidate was administered. Finally, a recent study by Morein-Zamir, Nagelkerke, Chua, Franks, and Kingstone (2002) compared SSRT measures from both tasks in a within-subject design. The correlation between SSRT as computed from the stop signal task and a modified version of the tracking task was .84 and significant, implying a common mechanism mediating both stopping processes. Taken together, one can conclude that the present estimates of stopping performance are sufficiently close to those obtained using the stop signal paradigm.

Assumptions other than independence between stop and go are sometimes used in conjunction with race model in the stop signal procedure. One such assumption is the invariance of stopping times (Osman et al., 1986, but see De Jong et al., 1990). Logan and Cowan (1984) described a model that included variance in SSRT and were able to obtain estimates of it, hence the invariance assumption was known to be limited. Nonetheless, most studies assume invariance of stopping times, so as to obtain estimates of SSRT with greater ease (e.g., De Jong et al., 1990). The present results provide support to the claim that such assumptions should be treated with caution. We found SSRT to be affected by stop signal modality (see also Colonius et al., 2001, for a similar conclusion for eye movements), and in Experiment 2 this effect interacted with trial length. In Experiment 2, the shape of the distribution was also altered somewhat by stop signal modality. Cavina-Pratesi, Bricolo, Prior, and Marzi (2001) have recently demonstrated that SSRTs computed in the stop signal task were 14 ms faster when the signal to stop was the redundant flashing of two white discs than when it was a single disc. It is therefore evident that the stop processes can be speeded up by salient or easily processed stimuli. We interpret the signal modality effect as influencing factors like signal detection difficulty and not the stopping process itself. Nonetheless, effects on SSRT do indicate that factors such as the nature of the stop signal itself may threaten the assumption of invariance.

The nature of the stop signal has not been widely investigated. It may well be that not only will more salient stimuli lead to faster stopping, but that the relationship between the go and stop stimuli will also be found to be of importance. In the present study, the go stimulus was always visual, while the stop signal modality was fixed to be either visual or auditory. At present it remains unclear whether the slower stopping times to visual signals could also in part result from the fact that the go stimulus was also visually presented. Typically, the stop signal is indeed auditory, and the go signal is visual, but it does not have to be the case.

In summary, the present results based on individual stopping times from a new stopping procedure supported the independence assumption between go and stopping processes. The findings also indicate that stopping may be more similar to other cognitive processes than previously suggested, and in the future it may even be found to be less unitary than currently assumed (Logan, 1994). In view of the fact that there is no clear account of stopping mechanisms (Band & van Boxtel, 1999; De Jong et al., 1995; Logan, 1994; McGarry & Franks, 2000), important insights may be gained by using continuous go tasks. In the future, it would also be beneficial to compare the two tasks and to examine whether possible dissociations could emerge.

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APPENDIX

Several additional analyses were conducted to examine the nature of the stopping process.

Analyses of undetermined SSRT trials where a lower criterion for stop was used successfully. These analyses aimed to shed light on why the algorithm failed to detect initial stopping in 22.2% and 33.2% of the trials for Experiments 1 and 2, respectively. One possibility is that the criterion of four consecutive increasing deviations may have been too strict. We therefore ran the algorithm on these trials employing a more lenient criterion of three consecutive increasing deviations. This resulted in the identification of initial stopping in about half of the analysed trials (10.5% and 14.7% of all trials, for Experiments 1 and 2, respectively). Due to the relatively small number of trials, the results were somewhat less clear. In the first experiment, while the results for tracking difficulty were analogous to the previous findings, this was not the case for trial length and signal modality. SSRT was faster on shorter trials (219 ms) than on longer trials (266 ms), and no significant effects involving stop signal modality were found. An ANOVA on SSRT revealed a significant main effect of trial length, $F(1, 11) = 15.31$, $p < .05$. An ANOVA on the newly defined SSDIS indicated a significant main effect of tracking difficulty, $F(1, 11) = 10.48$, $p < .01$ (26 vs. 36 pixels). In Experiment 2, SSRTs were longer for visual than for auditory stop signals (223 vs. 200 ms), but were also found to be shorter on easier trials than on more difficult trials (202 vs. 225 ms). The ANOVA on SSRT indicated a marginal effect for signal modality, $F(1, 11) = 3.3$, $p < .1$ and an effect for trial length, $F(1, 11) = 5.8$, $p < .05$.

Analyses of determined SSRT trials where reverses occurred. We were concerned that deviation from a linear cursor motion (which indicated initial stopping) could have resulted from a change in target trajectory. Nonetheless, the fact that SSRT was affected by stop signal modality in both experiments shows that it reflected stopping performance. A few trials in Experiment 1 were characterized by reverses before initial stopping (0.9%). Reverses were defined as a decrease in distance in observation N relative to observation $N - 1$. In order to refine the measure even further, we excluded these trials. The results were analogous to those reported in Analysis of Trials with Determined SSRT. No reverses were detected in the second experiment.

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