

On the Ability to Inhibit Simple and Choice Reaction Time Responses: A Model and a Method

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This article reports four experiments on the ability to inhibit responses in simple and choice reaction time (RT) tasks. Subjects responding to visually presented letters were occasionally presented with a *stop signal* (a tone) that told them not to respond on that trial. The major dependent variables were (a) the probability of inhibiting a response when the signal occurred, (b) mean and standard deviation (*SD*) of RT on no-signal trials, (c) mean RT on trials on which the signal occurred but subjects failed to inhibit, and (d) estimated RT to the stop signal. A model was proposed to estimate RT to the stop signal and to account for the relations among the variables. Its main assumption is that the RT process and the stopping process race, and response inhibition depends on which process finishes first. The model allows us to account for differences in response inhibition between tasks in terms of transformations of stop-signal delay that represent the relative finishing times of the RT process and the stopping process. The transformations specified by the model were successful in group data and in data from individual subjects, regardless of how delays were selected. The experiments also compared different methods of selecting stop-signal delays to equate the probability of inhibition in the two tasks.

In many real-world situations, we are interrupted in the middle of doing something, and we must stop and do something else. Sometimes we must react to changes in the input we are processing (e.g., checking an elusive player in sports); sometimes we must adjust to perturbations in the environment (e.g., stumbling or talking with our mouths full); and sometimes we must compensate for our own errors (e.g., slips of the tongue or mistakes in music). The ability to inhibit one action to begin another can be important to survival (e.g., dodging large falling objects), and speed is often crucial. Despite its ecological validity and significance, little is known about the ability to inhibit actions and little is known about the factors that determine the speed of inhibition.

It is possible to capture the essence of situations that require inhibition by engaging subjects in a reaction time (RT) task and occasionally presenting a *stop signal* that tells them to inhibit their response (see Lappin & Eriksen, 1966; Lisberger, Fuchs, King, & Evinger, 1975; Logan, 1981, 1982, 1983; Ollman, 1973; Welford, 1952). The major dependent variable is the probability of inhibiting the response, given a stop signal, which varies as a function of the difficulty of the RT task (Lisberger, et al., 1975; Logan, 1981, 1983), the subjects' strategy (Lappin & Eriksen, 1966; Logan, 1981; Ollman, 1973), and the delay between the onset of the RT stimulus and the onset of the stop signal (Lappin & Eriksen, 1966; Lisberger et al., 1975; Logan, 1981, 1982, 1983; Ollman, 1973; Slater-Hammel, 1960). This article presents a model of the response inhibition process that accounts for the effects of these factors on the probability of inhibition and relates them to each other, providing a basis for comparing the probability of inhibition in different conditions, tasks, strategies, and subjects. The model is different

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from most current theories of performance in situations in which two signals must be processed in rapid succession (e.g., Kantowitz, 1974; Posner & Boies, 1971; Welford, 1952) because it assumes there is no interference between the processes responding to the RT stimulus and the processes responding to the stop signal. This is important because it suggests that response inhibition is not subject to capacity limitations that prevail in other dual-task situations.

The model also provides a rationale and a method for estimating RT for the internal response to the stop signal. This is important because the response to the stop signal is not directly observable, and its RT cannot be estimated without a theory of response inhibition. The estimates of stop-signal RT suggest there is little interference between the processes responding to the RT stimulus and the processes responding to the stop signal: Stop-signal RT is very fast and relatively uninfluenced by stop-signal delay, in contrast to the long RTs and strong effects of delay in studies that require overt responses to similar signals (e.g., Kantowitz, 1974; Posner & Boies, 1971; Welford, 1952).

The Model

The model of response inhibition assumes that the processes responding to the RT stimulus race against the processes responding to the stop signal. If the processes responding to the stop signal finish first, the RT response will be inhibited; if the RT processes finish first, the response will be executed. The finishing times of the RT processes and the stopping processes are assumed to be independent and to vary randomly over trials. Thus, response inhibition will be probabilistic, reflecting the probability that the stopping processes will finish before the RT processes. The model also has implications for the latency of responses that escape inhibition.

Inhibition Functions

The major factors determining the probability of inhibiting a response can be seen in Figure 1. The top panel shows the onset of the stimulus for the primary (RT) task, the distribution of finishing times for the primary task, the onset of the stop signal, and the av-

erage finishing time for the processes that respond to the stop signal. (For ease of exposition, we assume that RT to the stop signal has no variability. A formal analysis in which RT to the stop signal was allowed to vary led to the same conclusions; see Logan & Cowan, in press.)

According to the model, whether or not a response is inhibited depends on relative finishing times of the processes responding to the stop signal and the processes responding to the primary task. This is represented in Figure 1 by the vertical line extending upward from the point at which the response to the stop signal occurs. On the left side of the line, the response to the primary task is faster than the response to the stop signal, and the subject responds. The area under the primary-task RT distribution to the left of the line represents the probability of responding to the primary task given a stop signal. On the right side of the line, the response to the stop signal is faster than the response to the primary task, and the subject inhibits his or her response. The area under the distribution to the right of the line represents the probability of inhibiting the primary-task response given a stop signal.

From Figure 1, it is apparent that at least four factors determine the relative finishing times of the primary task and the stopping task: (a) the delay between the onset of the stimulus for the primary task and the onset of the stop signal (*stop-signal delay*), (b) the mean RT to the primary task, (c) the mean RT to the stop signal, and (d) the variance of RT to the primary task. The effects of stop signal delay can be seen by comparing the top panel of Figure 1 with the second panel, in which the stop signal is delayed relative to the top panel. The response to the stop signal cuts off more of the primary-task RT distribution in the second panel than in the top panel, decreasing the probability of inhibition. These effects have been observed in a variety of tasks (e.g., simple RT, see Lappin & Eriksen, 1966; Ollman, 1973; choice RT, see Logan, 1981, 1983; eye movements, see Lisberger et al., 1975; typewriting, see Logan, 1982; anticipation, see Slater-Hammel, 1960).

The effects of varying mean primary-task RT can be seen by comparing the top panel of Figure 1 with the third panel, in which primary-task RT is longer. The response to the

stop signal cuts off less of the distribution in the third panel than in the top panel, increasing the probability of inhibition. These effects have been observed in studies of choice RT (Logan, 1981, 1983), eye movements (Lisberger et al., 1975), and typewriting (Logan, 1982).

The effects of varying RT to the stop signal

can be anticipated. Increasing stop signal RT should decrease the probability of inhibition and vice versa. However, the response to the stop signal is not directly observable, so its RT must be inferred. The model depicted in Figure 1 suggests a method: If we know the probability of inhibition and the distribution of primary

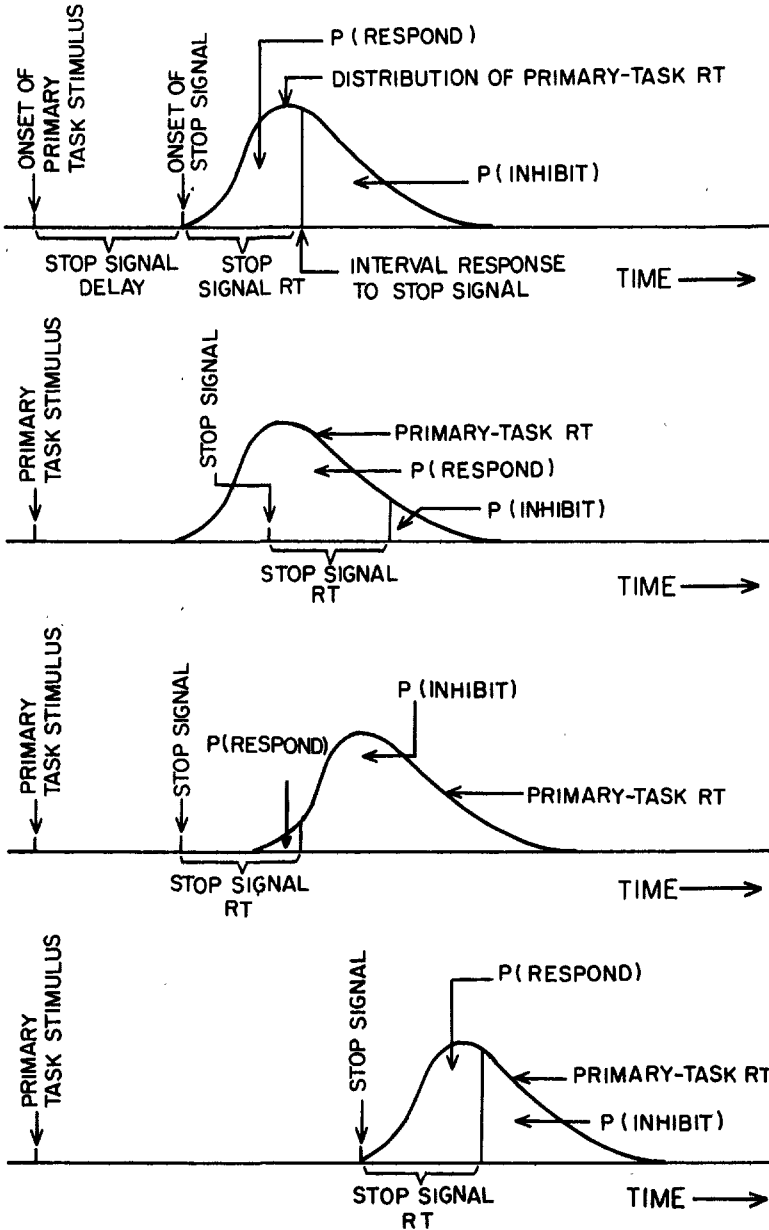


Figure 1. Graphic representation of the race model, accounting for the probability of inhibition, $P(\text{inhibit})$, and the probability of responding given a stop-signal, $P(\text{respond})$, in terms of the distribution of primary-task RTs, stop-signal RT, and stop-signal delay.

task RT, we can estimate the point in time at which the response to the stop signal occurred by integrating the RT distribution until the integral equals 1 minus the probability of inhibition. In Figure 1, this amounts to moving a vertical line from left to right across the RT distribution until the area to the right of the line equals the probability of inhibition and then reading the value on the time axis. Once we have determined the point in time at which the response to the stop signal occurred, we can estimate stop-signal RT by subtracting out stop-signal delay. This method has been applied in studies of choice RT, yielding estimates of stop-signal RT between 200 ms and 250 ms that did not vary much between conditions (Logan, 1981; Logan & Cowan, in press). The same method applied to simple RT yielded estimates in the same range (Lappin & Eriksen, 1966). Note that these estimated RTs are considerably faster than simple RTs to tones in dual-task studies (e.g., Kantowitz, 1974; Posner & Boies, 1971), suggesting that the response to the stop signal is not subject to the refractory effects observed with overt responses.

The effects of the variance of primary-task RT can be seen by comparing the top panel of Figure 2 with the bottom panel. Two lines have been drawn across the distributions representing two different finishing times for responses to the stop signal. By comparing the probability of inhibition at the two different finishing times in the two panels, we can see the effects of primary-task RT variance. The probability of inhibition increases faster as stop-signal finishing time increases in the bottom panel, which has the smaller variance, than in the top panel, which has the larger variance. Thus, primary-task RT variance affects the slope of the function relating the probability of inhibition to stop-signal delay. These effects have been observed in a choice RT task in which variance differed between individuals (Logan & Cowan, in press).

Before turning to the studies themselves, one more prediction must be developed, and it is the most important: The model predicts that situations that differ in mean RT, stop signal delay, and so on will produce equivalent probabilities of inhibition as long as the relative finishing times of their primary-task processes and stopping-task processes are equivalent.

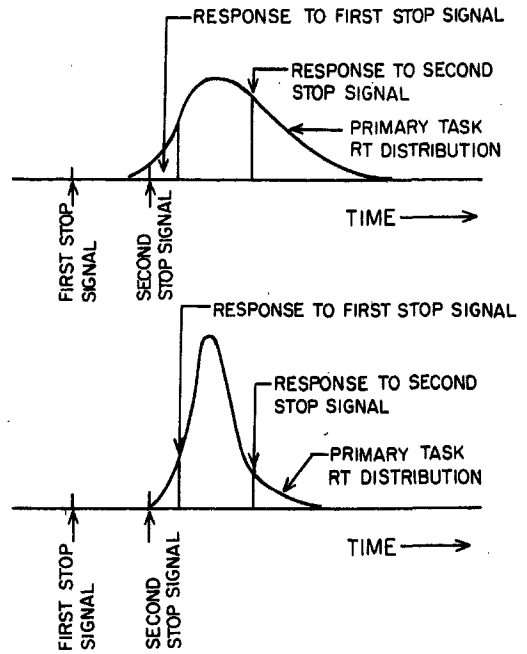


Figure 2. The effects of primary-task variance on the probability of inhibition.

This means it should be possible to compensate for differences in one of the four factors by making corresponding changes in one or more of the other factors to produce the same probability of inhibition. For example, differences in primary-task RT could be compensated for by increasing stop-signal delay by an amount corresponding to the difference in RT. This is shown in the bottom panel of Figure 1. Mean RT is increased, relative to the top panel, but delay has increased by a corresponding amount, so the probability of inhibition remains the same.

In general, it should be possible to account for differences in the probability of inhibition between conditions, subjects, and so on by plotting the probability of inhibition as a function of relative finishing time (RFT). According to the model, relative finishing time represents the point on the primary-task RT distribution at which the internal response to the stop signal occurs (see Figure 1), which may be expressed as a Z score:

$$ZRFT = \frac{\text{Primary-task RT} - \text{Delay} - \text{Stop-signal RT}}{SD \text{ of primary-task RT}}$$

The model predicts that inhibition functions from different conditions, tasks, subjects, and so on should be aligned when plotted against ZRFT. However, if the situations being compared do not differ much in the mean or the variance of primary-task RT or in stop-signal RT, it should be possible to bring the inhibition functions into alignment by plotting them against an approximation to ZRFT that takes into account only those factors that differ between the situations.

Four studies in the literature have plotted the probability of inhibition as a function of relative finishing time, and in each one the data from conditions that differed in primary-task RT and stop-signal delay lined up as if they were generated by the same function, just as the model predicts. This was found in studies of eye movements (Lisberger et al., 1975), typewriting (Logan, 1982), and choice RT (Logan, 1981, 1983), suggesting that the model applies to many different situations.

These studies indicate that stop-signal delay and the mean of primary-task RT are the most potent variables: Stop-signal RT was calculated in only three studies, and it did not vary much between conditions (Lappin & Eriksen, 1966; Logan, 1981; Logan & Cowan, in press). Primary-task variance was either not calculated or did not vary much between conditions. Relative finishing time, expressed simply as the difference between primary-task RT and stop-signal delay (i.e., $RT - \text{delay}$), accounted for nearly all the variance in the probability of inhibition.

Signal-Respond RT

The model also makes predictions about RT on those trials on which a signal occurs but the subject responds anyway (*signal-respond* trials): It predicts that the mean signal-respond RT should be faster than the mean RT on trials on which no signal occurs (*no-signal* trials), and it predicts that signal-respond RTs should increase with stop-signal delay. The basis for these predictions can be seen in Figure 1. The mean signal-respond RT corresponds to the mean of the part of the RT distribution that is to the left of the line representing the internal response to the stop signal. It is necessarily faster than the mean of

the entire distribution because it excludes the slow upper tail (i.e., the area to the right of the line representing the internal response to the stop signal). The effects of stop-signal delay can be seen by comparing the top panel of Figure 1 with the second panel, in which stop-signal delay is increased. The longer stop-signal delay cuts off more of the RT distribution and includes longer RTs in the calculation of the mean. Thus, mean signal-respond RTs should increase with stop-signal delay.

In the studies that reported them, signal-respond RTs were generally faster than no-signal RTs, and they generally increased with delay (Lappin & Eriksen, 1966; Lisberger et al., 1975; Logan, 1981, 1983; Logan & Cowan, in press).

The Experiments

The purpose of the present experiments was to see what is necessary to bring into alignment inhibition functions from tasks that differ widely in the mean and variance of RT. To achieve our purpose, we compared *simple* and *choice* RT. Subjects were shown letters and were asked to make speeded responses to them. In the simple RT task, they made the same response to every letter; in the choice RT task, they had to discriminate among the letters, making one response to half of them and another response to the other half. Under these conditions, simple RTs should be considerably faster and much less variable than choice RTs (see Logan, 1980; Woodworth & Schlosberg, 1954).

We considered three transformations of delay. The first was $RT - \text{delay}$, which represents the time between the onset of the stop signal and the expected occurrence of the RT response in milliseconds. We included it because of its past success in bringing inhibition functions into alignment (Lisberger, et al., 1975; Logan, 1981, 1982, 1983), but we expected it to fail in the present experiments because it cannot remove differences in variance.

The second transformation we considered was $(RT - \text{delay})/SD$, which represents the interval between the onset of the stop signal and the expected occurrence of the RT response in standard deviation units. We first thought that expressing $RT - \text{delay}$ in standard

deviation units would remove differences in variance, but we soon realized that the model predicts that functions should not be aligned by this transformation. Instead, it predicts that they should differ in proportion to differences in $SSRT/SD$ (stop-signal reaction time divided by standard deviation units). In the end, we included $(RT - \text{delay})/SD$ to demonstrate that not every transformation would bring the functions into alignment; only those specified by the model should work.

The third transformation we considered was $ZRFT = (RT - \text{delay} - SSRT)/SD$, which represents the interval between the finishing time of the stopping process and the expected occurrence of the RT response in standard deviation units. According to the model, this transformation should remove all of the differences between inhibition functions due to differences in stop-signal RT and the mean and variance of primary-task RT. We expected that ZRFT would be sufficient to account for the differences we would observe in our experiments; we compared it with the other transformations to determine whether it was necessary as well as sufficient.

Four experiments were conducted, each in two halves. In one half, a group of 12 subjects performed the tasks in a single session; in the other half, 2 subjects each performed the task for six sessions. The purpose was to determine whether the inhibition functions could be brought into alignment in the same way for groups of relatively unpracticed subjects as for individual, well-practiced subjects.

The experiments differed primarily in the manner in which the delays were selected. In Experiment 1, delays were selected arbitrarily and were the same for each subject throughout the experiment. In Experiments 2-4, delays were adjusted dynamically from block to block in order to hold constant various transformations of delay and thereby produce equivalent levels of inhibition in the simple and choice RT tasks. In Experiment 2, delays were selected so that different tasks and different subjects had the same values of $RT - \text{delay}$; in Experiment 3, delays were selected so that different tasks and different subjects had the same values of $(RT - \text{delay})/SD$; in Experiment 4, delays were selected so that different tasks and different subjects had the same values

of ZRFT. Apart from differences in the way delays were selected, the experiments were very similar in method, so they will be described together in a single method section.

Method

Subjects. Subjects were recruited from a "summer subject pool" that consisted of laboratory assistants, university students, and senior high-school students. Twelve served for a single session in the group version of each experiment, and 2 served for six sessions each in the individual version of each experiment. No subject served in more than one experiment.

Apparatus and stimuli. The stimuli for the simple and choice RT tasks were the letters E, F, H, and L, written in capitals by illuminating about 20 points in a 5×7 dot matrix on a CRT (Tektronix Model 604 equipped with P31 phosphor) controlled by a PDP 11/03 laboratory computer. The letters were presented one at a time in the center of the CRT screen. Viewed at a distance of 60 cm, the letters subtended about 0.57° vertically by 0.43° horizontally. The letters were exposed for 500 ms and were preceded by a 500-ms warning interval in which a fixation point (a single dot) was illuminated in the center of the screen. A 2.5-s intertrial interval began after the letter was turned off.

Subjects responded by pressing one of the two rightmost telegraph keys in a panel of eight mounted on a board in front of them. In the simple RT task, they pressed the rightmost key with the index finger of their right hand. In the choice RT task, they pressed the next-to-rightmost key with the index finger of their right hand to indicate that one of two letters had appeared, and they pressed the rightmost key with the middle finger of their right hand to indicate that one of the other two letters had appeared. The rules for mapping letters onto response keys will be discussed below.

The stop signal was a 500-ms, 900-Hz tone played through a speaker behind the CRT at a comfortable listening level. The stop signal began at one of four delays in each task. The values of the delays and the manner in which they were chosen differed between experiments. The details are provided in the next section.

Procedure. Each experimental session consisted of eight blocks of trials. The simple RT task was performed for four consecutive blocks, as was the choice RT task. The order in which the tasks were performed was balanced between subjects in the group version of each experiment and balanced within subjects in the individual version (each subject alternated orders over sessions, and the two subjects in each experiment began the first session with different tasks).

In Experiment 1, there were 80 trials in each block. Stop signals were presented on 20% of the trials, occurring equally often at each delay. Thus, there were 64 stop-signal trials per task each session, 16 at each delay. Stop-signal delays were fixed for each task and each subject. In the simple task, the signal occurred either 50, 100, 150, or 200 ms after the onset of the letter; in the choice task, the signal occurred either 100, 200, 300 or 400 ms after the onset of the letter.

In Experiments 2, 3, and 4, there were 100 trials in each block, and stop signals occurred on 24% of the trials, equally often at each delay. Because delays were adjusted dynamically in these experiments, the first block was used to estimate parameters to calculate the delays for the second block. Experiments 2 and 3 did not require estimates of SSRT, so stop signals were not presented in the first block for each task. Stop signals were presented in all blocks of Experiment 4, but only the last three blocks were analysed to make the data comparable to Experiments 2 and 3. Thus, in Experiments 2, 3, and 4, there were 72 stop-signal trials per task each session, 18 at each delay.

In Experiment 2, delays were adjusted each block so that stop signals would occur 300, 200, 100, or 0 ms before the expected occurrence of the RT response. Mean RT was calculated in the first block with each task and used to set delays for the next block equal to RT-300, RT-200, RT-100, and RT-0 ms. Mean RT for the second block was used to set the delays for the third block, and mean RT for the third block was used to set the delays for the fourth block. Thus, the delays for a given block depended only on performance in the immediately preceding block. This was true for Experiments 3 and 4 as well.

In Experiment 3, delays were adjusted dynamically so that the stop signal would occur 3, 2, 1, or 0 standard deviation units before the expected occurrence of the RT response. Mean and *SD* of RT were calculated in the first block and used to set values of $(RT - \text{delay})/SD$ equal to 3, 2, 1, and 0 for the second block. Mean and *SD* of RT for the second block were used to calculate delays for the third block, and so on as in Experiment 2.

In Experiment 4, delays were adjusted dynamically so that the internal response to the stop signal would occur 2, 1, 0, or -1 *SD* units before the expected occurrence of the RT response. The delays for the first block were set at -200 , -100 , 0, and 100 ms for the simple task and at 10, 130, 250, and 370 ms for the choice task. Mean and *SD* of RT were calculated and SSRT was estimated at each delay and then averaged, and the three were put together so that $ZRFT = (RT - \text{delay} - SSRT)/SD$ would equal 2, 1, 0, and -1 for each task. Parameters from the second block were used to set the delays for the third block, and so on. For the individual subjects, the delays for the first block in each task on the second and subsequent sessions were set using parameters calculated from the last block of the previous session.

In each experiment, the four stimulus letters occurred equally often in each block, and stop signals at each delay occurred equally often with each letter. The sequence of letters, stop signals, and stop-signal delays was random. A different random order was prepared for each subject each block.

In the choice task, the mapping of stimuli onto responses was balanced between subjects or between sessions. All six possible mappings of four letters onto two responses were used. In the group studies, each mapping was assigned to 2 subjects, one of which received the choice task before the simple and one of which received the opposite. In the individual studies, each subject received a different mapping each session for six sessions. The two subjects in each experiment cycled through the mapping rules in opposite directions.

The instructions described the first RT task before describing the stopping task. Subjects were told to respond to the RT task as quickly and accurately as possible without

anticipating the stimulus. They were then told to try to stop their response to the RT task if they heard a stop signal. They were told not to wait for the stop signal before responding; they were also told that we had selected delays such that some of the time they would be able to inhibit their responses and some of the time they would not. Thus, they were to protect the RT task from interference from the stopping task, as if the RT task were primary.

Results and Discussion

No-signal trials. The mean RTs, standard deviations, and accuracy scores for each task in each experiment are presented in Table 1. The characteristic differences between simple and choice RT emerged in each experiment. Simple RT was always faster than choice RT, $F(1, 44) = 373.15$, $p < .01$ ($MS_e = 4290.95$) and tended to be less variable, $F(1, 44) = 59.64$, $p < .01$ ($MS_e = 578.49$). The choice RTs were typical of the task (Woodworth & Schlosberg, 1954). The simple RTs for the group and Subject J.M. in Experiment 1 were longer than the 200 ms that is typical of simple RT tasks (Woodworth & Schlosberg, 1954) and longer than the simple RTs in the other experiments. Perhaps the group and Subject JM delayed their simple RTs deliberately to increase the likelihood of inhibiting their responses (cf. Lappin & Eriksen, 1966; Logan, 1981; Ollman, 1973).

The individual, practiced subjects often had simple RTs faster than 200 ms, which suggests they may have anticipated the stimulus. Indeed, the foreperiod was always 500 ms, so they could reliably predict when the stimulus would appear. The possibility that subjects may have anticipated the simple RT stimulus presents no problem from our perspective. We ran the simple RT task to tap a process that is faster and less variable than the choice RT processes, and anticipation is a satisfactory alternative.

In Experiment 1, the delays were independent of subjects' performance on no-signal trials, whereas in Experiments 2-4, the delays depended on various parameters of no-signal performance. Subjects may have been sensitive to the dependence and adjusted their performance to exert some control over the delays they would experience. To assess this possibility, we compared performance in the experiments in which delays were dependent with performance in the experiments in which delays were independent.

Table 1
 Mean Reaction Times (in ms), Standard Deviations, and Proportions of Correct Responses (in %) in the No-Signal Data From Each Experiment

Subject	Choice RT			Simple RT		
	RT	SD	% correct	RT	SD	% correct
Experiment 1						
Group	582	168	96	383	114	100
JM	491	140	94	357	142	100
RL	484	170	95	140	100	100
Experiment 2						
Group	509	123	97	216	84	100
LL	416	78	97	174	67	100
LU	428	90	95	196	69	100
Experiment 3						
Group	512	118	96	264	99	100
EL	404	92	98	119	75	100
KD	397	97	97	149	68	100
Experiment 4						
Group	514	121	97	221	81	100
MP	372	85	95	108	50	100
PB	448	139	92	105	56	100

The mean RTs in Experiments 2–4, in which delays depended on mean RT, were faster than the mean RTs in Experiment 1, in which delays were independent of mean RT, $F(1, 44) = 34.95$, $p < .01$ ($MS_e = 12558.51$). The individual subjects showed a similar difference. This difference could reflect subjects' sensitivity to the dependence of delay on mean RT, but it could also reflect a difference in the amount of practice subjects had with the tasks. There were 400 trials per task each session in Experiments 2–4, and the first 100 trials were excluded from analysis. By contrast, there were only 320 trials per task each session in Experiment 1, and all of them were analysed, including the first 100 trials. However, mean RTs for the first blocks of each task in Experiments 2–4 were still faster than the mean RTs in Experiment 1 (mean RT for the first 100 trials in Experiments 2–4 was 242 ms for the simple task and 519 ms for the choice task). This suggests that neither practice nor sensitivity to the dependence between mean RT and delay was responsible for the difference between Experiment 1 and Experiments 2–4 (recall that no stop signals were presented in the first blocks of each task in Experiments 2 and 3, so there was no dependence for subjects to be sensitive to).

Delays depended on SD in Experiments 3 and 4, and SD in the group data was not much

different from SD in the group data of Experiments 1 and 2, in which delays were independent of SD . A contrast comparing Experiments 1 and 2 with Experiments 3 and 4 was significant $F(1, 44) = 13.99$, $p < .01$ ($MS_e = 2145.174$), but it was not significant when Experiment 1 was excluded from the analysis, $F(1, 44) < 1$ ($MS_e = 2145.17$). The individual subjects showed the same weak effects.

The relatively small differences between experiments suggest that subjects were relatively insensitive to the dependency between delay and parameters of no-signal performance. The different methods for selecting delays seem relatively unobtrusive and transparent to the subject (also see Logan, 1982).

Stop-signal RT. The latency of the internal response to the stop signal was estimated for each task and delay for each subject in each experiment using the no-signal RT distribution and the probability of inhibition in the manner described above. The mean values for the group and for the two practiced subjects in each experiment are presented in Table 2.

There were two main trends in the data. First, stop-signal RT tended to be longer in the choice task than in the simple task. This was true for the group and for the practiced subjects in each experiment, though the effect was relatively weak in Experiments 2 and 3.

Table 2
Estimated Reaction Times (in ms) to the Stop Signal in Each Experiment

Subject	Choice RT				Simple RT			
	D1	D2	D3	D4	D1	D2	D3	D4
Experiment 1								
Group	284	255	221	204	263	223	199	182
JM	227	195	173	202	204	188	161	150
RL	241	228	192	165	202	194	157	155
Experiment 2								
Group	226	166	219	155	250	182	165	83
LL	199	163	173	153	218	207	152	138
LU	210	151	145	158	208	146	135	225
Experiment 3								
Group	258	188	212	155	251	216	192	166
EL	243	198	233	155	186	177	266	154
KD	228	197	181	188	189	191	179	150
Experiment 4								
Group	308	259	213	223	268	243	216	182
MP	233	211	150	186	114	111	160	181
PB	243	183	169	178	184	174	162	159

Note. D = delay.

The difference in stop-signal RT may reflect competition for resources between the stopping task and the RT tasks. Choice RT demands more resources than simple RT (Logan, 1980), and so may interfere more with the response to the stop signal. Note, however, that stop-signal RTs are relatively fast compared to simple RTs in dual-task situations (Kantowitz, 1974; Posner & Boies, 1971), suggesting that resource competition between the stopping task and the RT tasks was relatively weak.

The second effect was the tendency for stop-signal RT to decrease as delay increased. A decrease was observed in the group data and in the individual subject data in each experiment, though it was not always monotonic (e.g., Experiments 2, 3, and 4), and in Experiment 4, Subject MP's stop-signal RTs tended to increase with delay in the simple task. The decrease with delay stands in apparent contrast with the assumption in the simplified model presented above that stop-signal RT is constant. However, it is possible to account for the decrease by assuming that stop-signal RT has a constant mean and a nonzero variance. If that were so, the decrease would result from different portions of the stop-signal RT distribution winning the race at different delays. At short delays, most stop-signal RTs would be fast enough to win the race with the primary task, so the average stop-signal RT estimated from the data would be

about the same as the mean of the underlying distribution. At longer delays, only the faster stop-signal RTs would be fast enough to win the race, and the average stop-signal RT estimated from the data would be considerably faster than the mean of the underlying distribution. Thus, the observed stop-signal RTs would decrease as delay increased even if the underlying mean stayed constant. However, we cannot prove the underlying mean stayed constant nor can we rule out alternative explanations decisively.

Stop-signal RTs were about the same in the different experiments, suggesting that the different ways of selecting delays did not influence the way the signal was processed. In particular, note that stop-signal RTs in Experiment 4 were not very different from the rest. In Experiment 4, delays depended on stop-signal RT, and subjects might have altered their response to the stop signal to exert some control over stop-signal delay. Apparently, they did not.

Inhibition functions. The probability of inhibiting a response on stop-signal trials is plotted in Figures 3, 4, 5, and 6 for Experiments 1, 2, 3, and 4, respectively, as a function of delay and various transformations of delay.¹

¹ The standard error of the mean probabilities was calculated for each experiment using the error term from a one-way ANOVA performed on all the data from the group version. The standard errors were .044, .034, .040, and

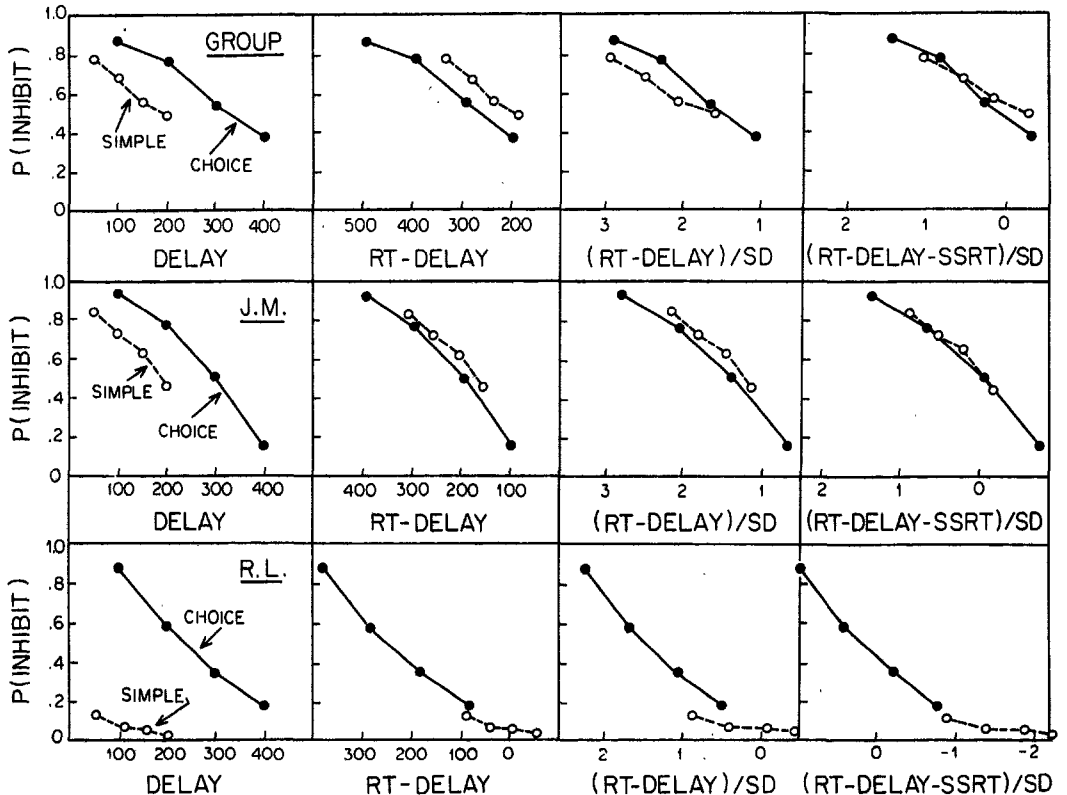


Figure 3. The probability of inhibition, $P(\text{inhibit})$, as a function of delay and its various transformations in Experiment 1. (The top row contains the group data, and the bottom two rows contain data from the two practiced subjects. Note: Delay was held constant over subjects and blocks; RT = primary-task reaction time; SD = standard deviation of primary-task RT; SSRT = stop-signal RT.)

A major purpose of the experiments was to compare the ability of the different transformations to bring the inhibition functions from the different tasks into alignment. The transformations had virtually the same effect in each experiment in both the group and the individual subject data: Inhibition functions for the choice task were substantially different from the functions for the simple task when plotted against delay. The functions were brought closer together when plotted against $RT - \text{delay}$, suggesting that the difference in no-signal RT accounts for a large part of the differences in the inhibition functions. There

were some discrepancies, however. The group data from Experiment 1 were not aligned very well (see Figure 3), and the functions for Subjects MP and PB in Experiment 4 differed markedly in slope when plotted against $RT - \text{delay}$ (see Figure 6).

Plotting the functions against $(RT - \text{delay})/SD$ did not improve the fit substantially and often made it worse. Consider, for example, the group data in Experiments 2–4 (see Figures 4–6) and Subjects LL (Experiments 2, Figure 4), KD (Experiment 3, Figure 5), and PB (Experiment 4, Figure 6). Recall that, according to the model, $(RT - \text{delay})/SD$ does not represent the relative finishing time of the RT process and the stopping process. Thus, the poor fit is consistent with the model. However, the fit was not always bad. It was better than the fit with any other transformation for Subject LU in Experiment 2 (see Figure 4).

The functions in each experiment aligned

.037 for Experiments 1–4, respectively. For each experiment, we determined the smallest difference between mean probabilities that would be significant at the .05 level, using Fisher's Least Significant Difference test (Kirk, 1968). The critical differences were .123, .096, .114, and .105 for Experiments 1–4, respectively.

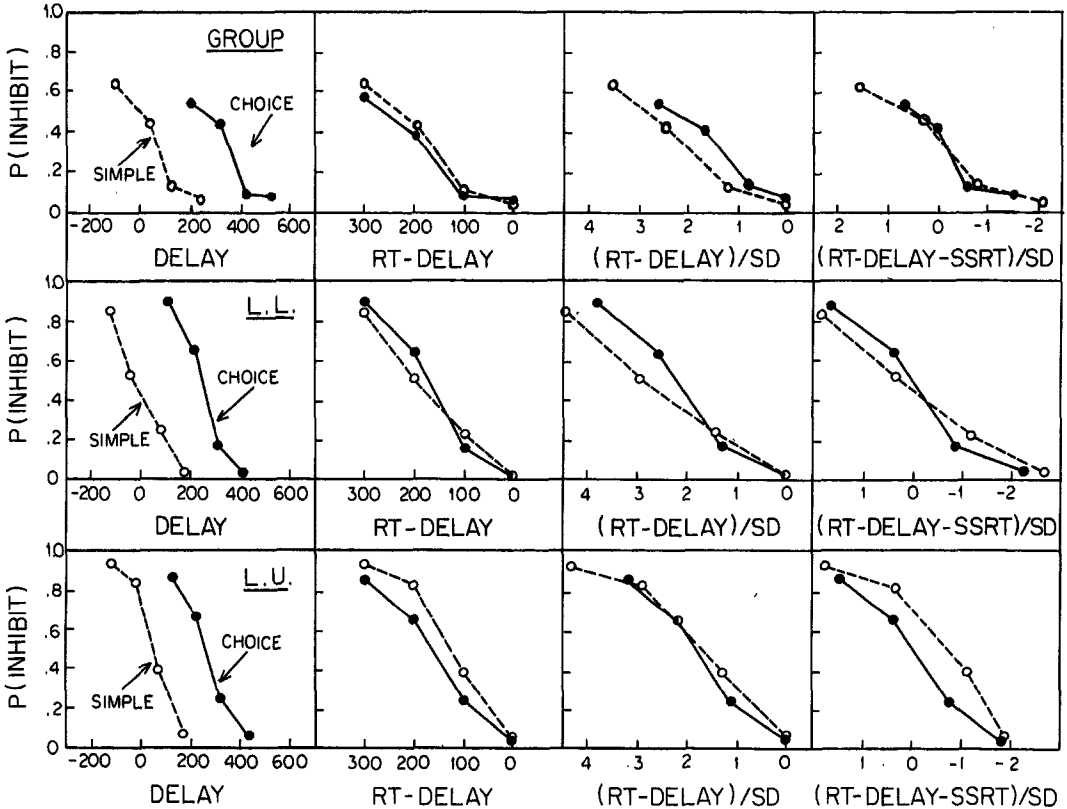


Figure 4. The probability of inhibition, $P(\text{inhibit})$, as a function of delay and its various transformations in Experiment 2. (The top row contains the group data, and the bottom two rows contain data from the two practiced subjects. Note: RT = delay was held constant over subjects and blocks; RT = primary-task reaction time; SD = standard deviation of primary task RT; SSRT = stop-signal RT.)

very closely when plotted against $ZRFT = (RT - \text{delay} - SSRT)/SD$. This was not surprising because the model predicts that ZRFT should be sufficient to align the functions. A major purpose of the experiments was to determine whether ZRFT was necessary by comparing it to the other transformations. Plotting the functions in terms of ZRFT improved the alignment relative to $(RT - \text{delay})/SD$ in each experiment, but it did not do much better than $RT - \text{delay}$. ZRFT seemed to be most successful when there were large differences in SD between simple and choice RT (e.g., Subjects MP and PB in Experiment 4, Figure 6).²

It was not possible to compare the different transformations of delay within each experiment using conventional statistical techniques such as analysis of variance (ANOVA). Instead, we performed two-way ANOVAs in each ex-

periment with tasks and delay or its transformation as factors. We should be able to assess statistically which transformations succeed in removing differences in tasks by comparing the results of the ANOVAs done on the different experiments.

In Experiment 1, in which delays were fixed, the simple and choice tasks had only two delays in common, 100 and 200 ms. Delay had a strong effect, $F(1, 11) = 14.48, p < .01 (MS_e = .016)$, but so did tasks, $F(1, 11) = 23.44, p < .01 (MS_e = .029)$, and the interaction between delay and tasks was significant, $F(1, 11) =$

² Note that the goodness of fit with ZRFT does not depend on a separate estimate of stop-signal RT for each delay. Stop-signal RTs from the different delays were averaged, and the average value was used to calculate ZRFT for each delay.

6.25, $p < .05$ ($MS_e = .005$). The latter two effects indicate that delay did not remove differences in the inhibition functions due to tasks.

In Experiment 2, in which $RT - delay$ was fixed, only the effect of $RT - delay$ was significant, $F(3, 33) = 92.30$, $p < .01$ ($MS_e = .014$); neither the effect of tasks, $F(1, 11) < 1$ ($MS_e = .011$) nor the interaction between tasks and $RT - delay$, $F(3, 33) < 1$ ($MS_e = .014$) was significant. The null effect of tasks and the null interaction suggest that $RT - delay$ was very successful in removing differences between inhibition functions due to tasks.

In Experiment 3, in which $(RT - delay)/SD$ was fixed, there were significant effects of $(RT - delay)/SD$, $F(3, 33) = 203.65$, $p < .01$ ($MS_e = .011$), and tasks, $F(1, 11) = 5.49$, $p < .05$ ($MS_e = .047$), and the interaction between

tasks and $(RT - delay)/SD$ was significant, $F(3, 33) = 53.54$, $p < .01$ ($MS_e = .019$). Here, the significant effects of tasks and the interaction between tasks and delay suggests that $(RT - delay)/SD$ was not very successful in removing differences due to tasks.

In Experiment 4, in which ZRFT was fixed, there was a significant effect of ZRFT, $F(3, 33) = 138.81$, $p < .01$ ($MS_e = .015$). The effect of tasks was not significant, $F(1, 11) = 1.11$ ($MS_e = .042$), and the interaction between tasks and ZRFT approached conventional levels of significance, $F(3, 33) = 2.60$, $p < .07$ ($MS_e = .011$). The null effect of tasks and the weak interaction between tasks and ZRFT suggest that ZRFT was successful in removing most of the differences due to tasks.

On the balance, then, the ANOVA results confirm the conclusions drawn earlier by visual

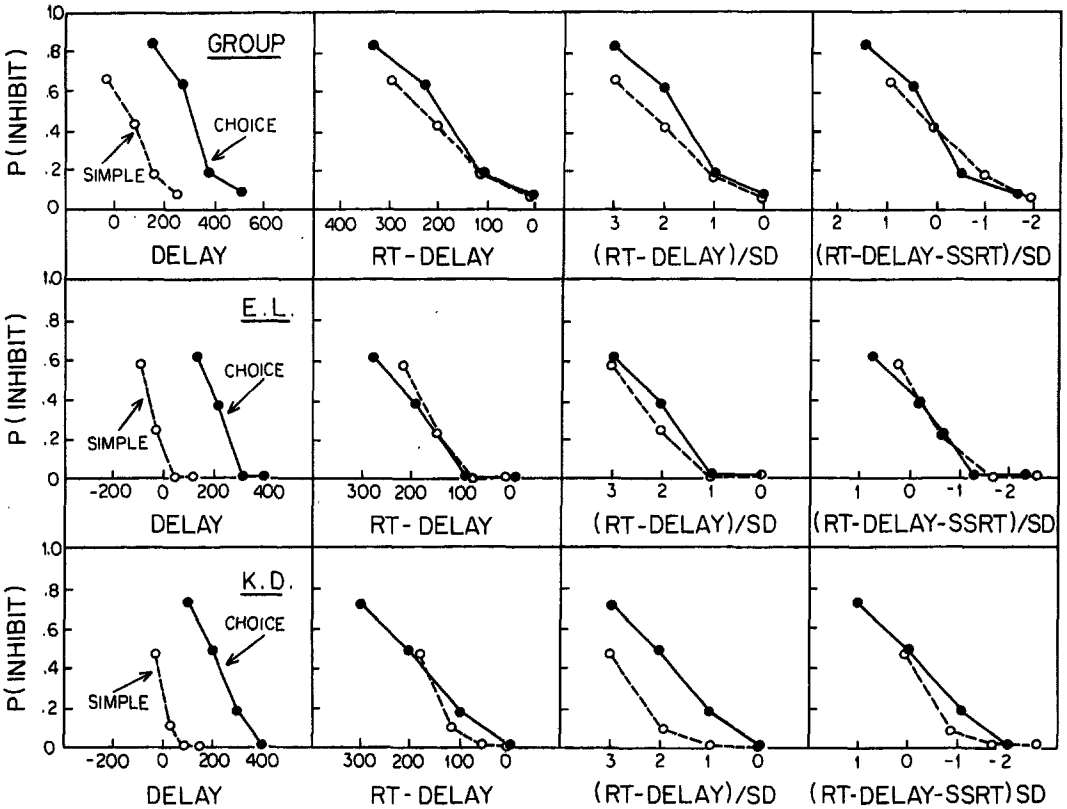


Figure 5. The probability of inhibition, $P(\text{inhibit})$, as a function of delay and its various transformations in Experiment 3. (The top row contains the group data, and the bottom two rows contain data from the two practiced subjects. Note: $(RT - delay)/SD$ was held constant over subjects and blocks; RT = primary-task reaction time; SD = standard deviation of primary-task RT; $SSRT$ = stop-signal RT.)

inspection: $RT - \text{delay}$ accounts for most of the differences between inhibition functions; $(RT - \text{delay})/SD$ makes matters worse; and ZRFT improves the fit, but it is not much better than $RT - \text{delay}$.

Signal-respond RT. Reaction times from trials on which a stop signal occurred but subjects responded anyway are presented in Table 3 as a function of delay and task for the group and the 2 practiced subjects in each experiment. According to the model, signal-respond RTs should be faster than no-signal RTs, and they should tend to increase with stop-signal delay. Both of these predictions were supported. First, for the group and for the practiced subjects in each experiment, the mean signal-respond RT was faster than the mean no-signal RT, suggesting that signal-respond RTs came from the fast tail of the no-signal RT distribution. Second, excluding the shortest

delay in the choice tasks where the means were based on the fewest observations, signal-respond RT tended to increase with delay for the group and the two practiced subjects in each experiment, as the model predicted. It is not clear why the shortest delays in the choice task produced the longest signal-respond RTs on occasion. Perhaps subjects occasionally "pulled" their responses when the signal occurred, making them more slowly with less force (cf. Rabbitt, 1978); there is evidence that some portions of a response are inhibited before others (Henry & Harrison, 1961). Nevertheless, the signal-respond RTs are generally consistent with the model.

General Discussion

The model was successful in accounting for the various response-inhibition phenomena

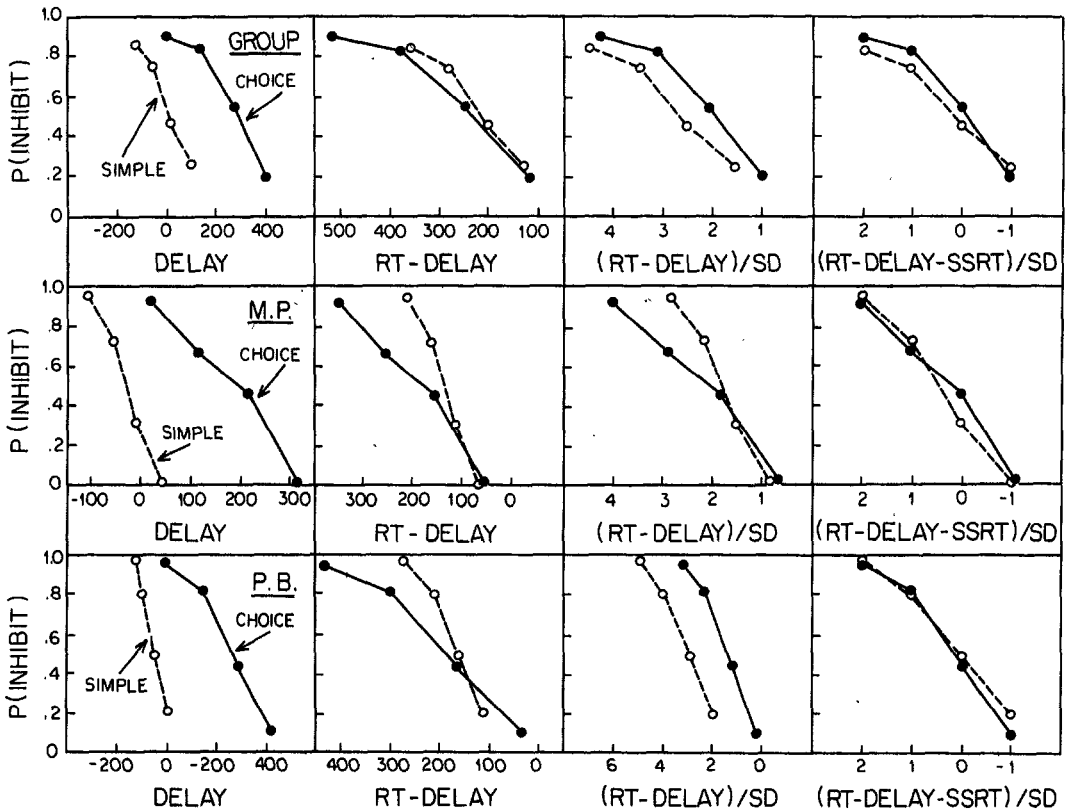


Figure 6. The probability of inhibition, $P(\text{inhibit})$, as a function of delay and its various transformations in Experiment 4. (The top row contains the group data, and the bottom two rows contain data from the two practiced subjects. Note: $ZRFT = (RT - \text{delay} - SSRT)/SD$ was held constant over subjects and blocks; RT = primary-task reaction time; SD = standard deviation of primary-task RT; $SSRT$ = stop-signal RT.)

observed in the experiments. First, it accounted for the probability of inhibition, bringing the inhibition functions for the different tasks into alignment when they were plotted against the transformations specified by the model (i.e., $RT - \text{delay}$ and ZRFT) but not when they were plotted against transformations that were not specified by the

model, that is, delay and $(RT - \text{delay})/SD$. It is interesting that the model was successful in bringing the inhibition functions into alignment because its success depended on the assumption that the stop signal was processed without interference from the RT processes. The null hypothesis of no interference between concurrent processes has been rejected in most

Table 3
Mean Reaction Times (in ms) and Percentage of Correct Responses
From Signal-Respond Trials in Each Experiment

Subject	Choice RT				Simple RT			
	D1	D2	D3	D4	D1	D2	D3	D4
Experiment 1								
Group								
RTs	440	349	568	512	185	355	259	294
% correct	63	61	93	96				
JM								
RTs	590	421	414	454	238	262	292	301
% correct	100	86	98	96				
RL								
RTs	478	409	407	437	99	129	129	131
% correct	92	100	95	95				
Experiment 2								
Group								
RTs	448	454	462	490	157	153	189	201
% correct	96	91	100	96				
LL								
RTs	364	356	402	407	91	118	149	172
% correct	100	100	97	99				
LU								
RTs	472	400	420	412	130	121	162	185
% correct	100	98	98	94				
Experiment 3								
Group								
RTs	438	467	462	488	171	196	220	244
% correct	100	97	95	95				
EL								
RTs	393	374	398	396	81	84	104	118
% correct	96	99	97	98				
KD								
RTs	336	322	368	376	128	134	124	143
% correct	94	99	91	97				
Experiment 4								
Group								
RTs	481	475	442	495	193	187	183	200
% correct	100	92	96	93				
MP								
RTs	320	298	347	340	115	61	74	91
% correct	100	98	96	89				
PB								
RTs	292	306	390	425	—	40	68	83
% correct	33	89	94	92				

Note. D = delay.

other studies of dual-task situations (e.g., Kantowitz, 1974; Posner & Boies, 1971; Wolford, 1952). Apparently, response inhibition is an exception to the general rule (also see Logan, 1981, 1982).

Second, the model allowed us to estimate reaction time for the internal response to the stop signal, which could not have been estimated without the model. The estimated stop-signal RTs were relatively fast and relatively free from dual-task interference. Stop-signal RTs did become faster as stop-signal delay increased, which could reflect a refractory effect from processing the RT stimulus (cf. Kantowitz, 1974), but the reduction with delay could also result from variability in stop-signal RT such that only the faster stop-signal RTs won the race with the primary task processes at the longer stop-signal delays (see Logan & Cowan, in press). In any event, the effects of delay were small relative to the effects of delay in situations that require overt responses to both tasks (see Kantowitz, 1974; Posner & Boies, 1971).

On the average, stop-signal RTs were 17 ms slower in the choice task than in the simple task, which might reflect resource competition between the stopping processes and the primary-task processes. Again, the effect was small relative to the interference observed when both tasks require overt responses (cf. Logan, 1980). Thus, it seems fair to conclude that the stop signal was processed without much interference from the primary task, as the model assumes.

Third, the model predicted that primary-task RTs that escaped inhibition (*signal-respond* RTs) should be faster than primary-task RTs from no-signal trials and should increase with stop-signal delay. Both of these predictions were confirmed in each version of each experiment, though the increase with delay was not always as clear as the difference between signal-respond and no-signal RTs. These predictions were also predicated on the assumption of no interference between the stopping processes and the primary-task processes, and their confirmation lends further credence to that assumption. The experiments, then, suggest response inhibition is an important exception to the general finding of interference between concurrent tasks and processes.

It is instructive to compare response inhi-

bition with other exceptions to the general finding of dual-task interference. Dual-task interference is often reduced in situations in which the two tasks are very compatible with each other (see Allport, 1980). Response inhibition is not an example of that type of situation because the response to the stop signal (stopping the primary-task response) is perfectly incompatible with the response to the primary task. Dual-task interference is also often reduced in situations in which the two tasks are practiced together extensively (e.g., Spelke, Hirst, & Neisser, 1976). Response inhibition is not an example of that type of situation either, because dual-task interference was absent even in the unpracticed subjects. It would seem that some new principles are necessary to explain the lack of dual-task interference in response inhibition studies.

Elsewhere, we argued that response inhibition phenomena are consistent with a hierarchical theory of attention in which a high-level process determines the significance of incoming stimuli and decides whether to abort the current stream of thought and action or to queue the new stimuli along with the old ones, to be processed as resources become available (Logan, 1982; Logan & Cowan, in press). This would account for the relatively quick response to a stimulus when it is a stop signal and the relatively slow response to the same stimulus when it requires an overt response. Hierarchical theories of attention have been proposed for other reasons (see e.g., Reason & Myceilska, 1982). Response inhibition phenomena and the acts of control they represent may be a further reason to pursue the notion of an attentional hierarchy.

In addition to testing the model, the experiments also evaluated different methods for selecting stop-signal delays to equate the probability of inhibition in different tasks, subjects, and so on. In Experiments 2-4, delays were adjusted dynamically from block to block to hold constant the values of the different transformations. Generally, inhibition functions were equated when delays were selected to hold constant the transformations specified by the model (i.e., $RT - \text{delay}$ and ZRFT) but not when delays were selected to hold constant transformations not specified by the model, that is, $(RT - \text{delay})/SD$.

The mean and variance of primary-task RT

and the estimates of stop-signal RT were relatively unaffected by the dynamic adjustment of stop-signal delay, suggesting that the process of adjustment was relatively transparent to the subjects. This means that the different methods can be used to obtain specified levels of response inhibition without substantially affecting the processes being inhibited. Dynamic adjustment may prove to be useful in exploring novel situations; in other cases, desired levels of inhibition can be obtained by setting delays to particular values of ZRFT.

References

- Allport, D. A. (1980). Attention and performance. In G. Claxton (Ed.), *Cognitive psychology* (pp. 112-153). London: Routledge & Kegan Paul.
- Henry, F. M., & Harrison, J. S. (1961). Refractoriness of a fast movement. *Perceptual and Motor Skills*, 13, 351-354.
- Kantowitz, B. H. (1974). Double stimulation. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 83-131). Hillsdale, NJ: Erlbaum.
- Kirk, R. E. (1968). *Experimental design: Procedures for the behavioral sciences*. Monterey, CA: Brooks/Cole.
- Lappin, J. S., & Eriksen, C. W. (1966). Use of a delayed signal to stop a visual reaction-time response. *Journal of Experimental Psychology*, 72, 805-811.
- Lisberger, S. G., Fuchs, A. F., King, W. M., & Evinger, L. C. (1975). Effect of mean reaction time on saccadic responses to two-step stimuli with horizontal and vertical components. *Vision Research*, 15, 1021-1025.
- Logan, G. D. (1980). Short-term memory demands of reaction time tasks that differ in complexity. *Journal of Experimental Psychology: Human Perception and Performance*, 6, 375-389.
- Logan, G. D. (1981). Attention, automaticity, and the ability to stop a speeded choice response. In J. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 205-222). Hillsdale, NJ: Erlbaum.
- Logan, G. D. (1982). On the ability to inhibit complex movements: A stop-signal study of typewriting. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 778-792.
- Logan, G. D. (1983). On the ability to inhibit simple thoughts and actions: I. Stop-signal studies of decision and memory. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 9, 585-606.
- Logan, G. D., & Cowan, W. B. (in press). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*.
- Ollman, R. T. (1973). Simple reactions with random countermanding of the "go" signal. In S. Kornblum (Ed.), *Attention and Performance IV* (pp. 571-581). New York: Academic Press.
- Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review*, 78, 391-408.
- Rabbitt, P. M. A. (1978). Detection of errors by skilled typists. *Ergonomics*, 21, 945-958.
- Reason, J., & Myceilska, K. (1982). *Absent minded: The psychology of mental lapses and everyday errors*. Englewood Cliffs, NJ: Prentice-Hall.
- Slater-Hammel, A. T. (1960). Reliability, accuracy, and refractoriness of a transit reaction. *Research Quarterly*, 31, 217-228.
- Spelke, E., Hirst, W., & Neisser, U. (1976). Skills of divided attention. *Cognition*, 4, 215-230.
- Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance: A review and a theory. *British Journal of Psychology*, 43, 2-19.
- Woodworth, R. S., & Schlosberg, H. (1954). *Experimental psychology* (2nd ed.). New York: Holt.

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