

# Dependence and Independence in Responding to Double Stimulation: A Comparison of Stop, Change, and Dual-Task Paradigms

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When a letter and a tone are presented in rapid succession, there is substantial interference if both require an overt response (the *dual-task* paradigm), but there is very little interference if the tone is a signal to inhibit the response to the letter (the *stopping* paradigm). These effects were replicated under common stimulus conditions in two experiments, and they were compared with effects in a *change* paradigm, in which the tone required an overt response, like the dual-task paradigm, but was also a signal to inhibit the response to the letter, like the stopping paradigm. In the change paradigm, the overt response to the tone suffered interference only if subjects failed to inhibit the concurrent response to the letter; inhibiting the response to the letter virtually eliminated the interference. The results suggest that differences in response competition are primarily responsible for differences in interference between the dual-task and stopping paradigms. More generally, the results support response-competition interpretations of dual-task interference.

In a typical *dual-task* experiment, people are presented with two stimuli in rapid succession and are required to respond to each stimulus as quickly as possible. Typically, there is substantial interference between the two tasks, particularly when the delay is short (see, e.g., Kahneman, 1973; Kantowitz, 1974; Welford, 1952). The interference is typically explained by models that assume strong dependence between tasks, due to competition for common resources or access to common processing mechanisms (e.g., Navon & Gopher, 1979; Schvickert & Boggs, 1984; Wickens, 1984). However, much of the interference can be removed by simply changing the instructions: A *stop-signal* experiment can involve the same stimuli and the same delays as a dual-task experiment, but the second stimulus tells the subject to inhibit the response to the first stimulus. As in the dual-task paradigm, each stimulus requires a distinct response, but there is virtually no interference between the two tasks (see, e.g., Logan, Cowan, & Davis, 1984). Performance in the stop-signal paradigm can be modeled accurately by assuming complete independence between the processes that respond to the *go* signal and those that respond to the *stop* signal (Logan & Cowan, 1984; Ollman, 1973).

The purpose of this article is to explore this remarkable

difference in interference in more detail. First, an attempt will be made to account for the difference in interference in terms of *response competition*, and response competition effects will be contrasted with the effects of competition for more central resources. Then the dual-task paradigm will be compared with the stopping paradigm directly, to replicate the differences in interference while using exactly the same stimuli and delays and using subjects from the same population. This has not been done in previous experiments, and the difference in interference would be less remarkable if it were due to subtle differences in the procedures of typical dual-task and stop-signal experiments. Finally, dual-task and stop-signal performance will be compared with performance in a *change* paradigm, in which there are two stimuli presented in rapid succession, and the second stimulus requires subjects to inhibit their responses to the first stimulus, like the stop-signal paradigm, and it also requires an overt response, like the dual-task paradigm. Thus, the change paradigm shares some features with the stop-signal paradigm and other features with the dual-task paradigm. It represents a procedural "bridge" that allows us to assess more directly the contrasting roles that response competition plays in the two paradigms.

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## Response Competition in Dual-Task and Stopping Paradigms

In general, response competition theories claim that the major bottleneck in processing occurs at the stage of selecting and executing responses. The basic idea underlies late-selection theories of attention (e.g., Deutsch & Deutsch, 1963; Keele & Neill, 1978; Norman, 1968) and has been applied to a wide variety of specific problems, including multiple-choice reaction time (Berlyne, 1957), Stroop interference (Keele, 1973), and dual-task interference (Herman & Kantowitz, 1970; Reynolds, 1964). In the dual-task literature, several lines of evidence point

to the importance of response competition. First, there is much more interference when two tasks require similar motor responses (e.g., both vocal or both manual) than when they require dissimilar responses (e.g., one vocal and one manual; see Logan, Zbrodoff, & Fostey, 1983; McLeod, 1978). Second, the refractory effect of a first task on a second is much stronger for response-related processes than for prereponse processes (Karlin & Kestenbaum, 1968; Pashler, 1984). Third, in many cases, dual-task interference is better predicted by the interval between the response to the first task and the stimulus for the second than by the interval between the first and second stimulus (Ninio, 1975).

There are a number of theoretical alternatives to response competition that assume that major bottlenecks in processing can occur before response selection and execution. Early-selection (Broadbent, 1958), single-capacity (Kahneman, 1973), and multiple-resource (Navon & Gopher, 1979; Wickens, 1984) theories of attention all share the assumption of a central bottleneck. Specific versions of these central-bottleneck theories have been developed to account for many of the phenomena that response competition accounts for, including dual-task interference. Several lines of evidence point to a central bottleneck in the dual-task paradigm. First, dual-task interference can be produced when the two tasks involve different response modalities (Davis, 1957). Second, dual-task interference is greater when the two tasks use the same input modality (e.g., two visual stimuli or two auditory stimuli) than when they use different input modalities (e.g., one visual stimulus and one auditory stimulus; see Proctor & Proctor, 1979; Treisman & Davies, 1973). Third, dual-task interference can be produced even when the stimuli and responses are widely separated in time (Logan, 1979).

Given the evidence for response competition and for a more central bottleneck, the best interpretation may be that both factors are responsible for dual-task interference. Thus, the appropriate question is which one is more important in a given situation. From this perspective, response competition may provide a better explanation of the difference in interference between the dual-task and the stop-signal paradigms. In the dual-task paradigm, the first and second stimulus both require overt responses, and the two responses may compete with each other for access to the motor system, producing interference. However, in the stop-signal paradigm, only the first stimulus requires an overt response; the response to the second stimulus (the stop signal) is covert. Thus, there is no response competition and no interference. A central-bottleneck theory could account for the difference by assuming that the dual-task paradigm was more demanding than the stop-signal paradigm, but the difference in demand would have to be substantial. It is difficult to see how the theory could argue for a large difference in demand on an a priori basis without admitting that the requirement to execute two responses versus one was primarily responsible for the difference in demand. It may be possible to argue for a difference in concurrence cost or for a difference in the demands of preparing for a dual-task trial versus a stop-signal trial, and thereby mimic the predictions of response competition theory.

The change paradigm is very interesting in this context because it allows us to distinguish clearly between response com-

petition and central bottleneck interpretations. When subjects fail to inhibit their response to the first stimulus (i.e., on *signal-respond* trials), the change paradigm is like the dual-task paradigm in that there are two stimuli and two overt responses. However, when subjects succeed in inhibiting their response to the first stimulus (i.e., on *signal-inhibit* trials), the change paradigm is like the stop-signal paradigm in that there are two stimuli but only one overt response. If response competition is the major factor contributing to the difference in interference between the dual-task and stopping paradigms, then signal-respond trials should produce exactly the same interference as the dual-task paradigm, and signal-inhibit trials should produce no interference.

A central bottleneck theory would predict interference on signal-respond trials, because they are like dual-task trials, but it should also predict some interference on signal-inhibit trials. It would be hard to argue that signal-respond and signal-inhibit trials differed in concurrence cost or in preparation because subjects cannot tell in advance whether they would inhibit the response to the first stimulus.

Response competition and a central bottleneck may both contribute to the difference in interference between the dual-task and stop-signal paradigms. In that case, the change paradigm will allow us to determine which contributes more. If signal-respond trials suffer substantially more interference than signal-inhibit trials do, then response competition will be the more important factor. However, if signal-respond and signal-inhibit trials suffer about the same amount of interference, then a central bottleneck will be the more important factor. Any difference in interference between signal-respond and signal-inhibit trials will reflect the contribution of response competition; any interference at all in the signal-inhibit condition will reflect the contribution of a central bottleneck.

## The Experiments

Two experiments were conducted. In both experiments, the first stimulus was a single letter, and the second stimulus was a tone. In all conditions of both experiments, the letter was drawn from one of two pairs, and the task was to indicate which set it came from. The response to the tone distinguished the different paradigms: In the dual-task paradigm, subjects made a separate overt response to the tone while concurrently responding to the letter. In the stopping paradigm, subjects tried to inhibit their response to the letter when they heard the tone. In the change paradigm, when the tone was presented, subjects tried to inhibit their responses to the letter and made a separate overt response to the tone.

In both experiments, the tone occurred at one of six delays after the onset of the letter (80, 160, 240, 320, 400, and 480 ms). In the dual-task paradigm and in those trials in the change paradigm on which subjects failed to inhibit their response to the letter, interference with the response to the tone should be greatest the shorter the delay between the letter and the tone (e.g., Kantowitz, 1974). In the stopping paradigm and in those trials in the change paradigm on which subjects succeeded in inhibiting their response to the letter, there should be no interference at any tone delay.

In addition to tone delay, the major manipulation in Experiment 1 was tone probability: Letter-only trials were mixed randomly with letter-plus-tone trials, and the relative frequency of letter-plus-tone trials was varied (20%, 50%, or 80% of the trials were letter-plus-tone trials). Tone probability was varied because it is an aspect of the procedure that is typically different in stop-signal and dual-task studies. In stop-signal studies, tone probability is usually low (10%–30%) so that subjects cannot easily anticipate the tone (see, e.g., Logan, 1981). However, dual-task studies often include blocks of trials that consist entirely of letter-plus-tone trials with letter-only trials run as a control condition in separate blocks of trials. When letter-plus-tone trials are mixed together with letter-only trials, tone probability is usually high (50% or more). In order to determine whether differences in tone probability were responsible for the differences in interference that are typically observed, the tasks were compared under the same tone probability conditions.

In Experiment 2 we manipulated tone delay and fixed tone probability at 50%. Its major manipulation was practice; subjects performed a total of 4,320 letter-only and letter-plus-tone trials over a period of 6 days. Dual-task interference can change dramatically with practice (e.g., Logan, 1979), whereas performance in the stop-signal paradigm seems relatively stable over practice (see Logan et al., 1984). Thus, it was important to compare the paradigms at several different stages of practice.

The two experiments shared common methods, so they will be described in a single Method section. For clarity of presentation, the description and discussion of the results will be organized around the various dependent measures (i.e., reaction time to the letter, reaction time for the overt response to the tone, internal reaction time to the stop signal) instead of by experiments.

## General Method

### Subjects

In Experiment 1 there were four different groups of 12 subjects, one group in the dual-task paradigm, one in the stopping paradigm, one in the change paradigm, and one that responded only to the tones as a single-task control. Each subject served for one 1-hr session. In Experiment 2 there were three different groups of 6 subjects, a dual-task group, a stopping group, and a change group. Each subject served for six 1-hr sessions. Subjects were undergraduate and graduate students and research assistants. Some subjects in Experiment 1 served to fulfill course requirements; others were paid \$4 per hour for participating. All subjects in Experiment 2 were paid.

### Apparatus and Stimuli

The stimuli for the letter task were the letters *A*, *B*, *C*, and *D*, displayed in upper case in the center of a point-plot cathode-ray tube (CRT; Technitron Model 604 equipped with P31 phosphor) under the control of a PDP 11/03 computer. Each letter was preceded by a fixation point displayed in the center of the screen for 500 ms. The fixation point was extinguished and replaced immediately by the letter for that trial, which was exposed for 500 ms. After the letter was extinguished, the screen remained blank for a 2,500-ms intertrial interval. Viewed at a distance of 60 cm, each letter subtended  $0.43^\circ \times 0.57^\circ$  of visual angle.

The tone was played at 900 Hz for 500 ms through a speaker located

behind the CRT. When the tone occurred, it began 80, 160, 240, 320, 400, or 480 ms after the letter began.

Subjects in all groups responded to the letter by pressing the rightmost or the next-to-rightmost of a panel of eight telegraph keys mounted on a movable board. Subjects in the dual-task and change groups responded to the tone by pressing the leftmost key in the panel of eight.

### Procedure

Each session involved 720 trials divided into six blocks of 120. Each letter occurred equally often in each block. Tones occurred equally often at each delay in each block, and each letter appeared equally often at each tone delay. In Experiment 1, tones were presented on 20%, 50%, or 80% of the trials in each block, which corresponds to 24, 60, and 96 trials, respectively. Subjects received two blocks at each tone probability before moving on to the next tone probability. The order of tone-probability conditions was varied between subjects; two subjects in each group received each of the six possible orders. In Experiment 2, tones were presented on 50% of the trials in each block (60 trials). A different random order of trials was prepared for each subject in each session of each experiment.

All subjects in each group of each experiment pressed the next-to-rightmost key in the panel of eight with the index fingers of their right hands to indicate that the letter was an *A* or a *B*, and they pressed the rightmost key with the middle fingers of their right hand to indicate that the letter was a *C* or a *D*. Subjects in the dual-task and change groups in each experiment and subjects in the tone-only group of Experiment 1 pressed the leftmost key in the panel of eight with the index fingers of their left hands to indicate that the tone occurred.

*Dual-task group.* Subjects in the dual-task group were first told about the events in the letter task and the responses that were appropriate to the different letters. Then the tone was described, and the response that was appropriate to it was described. They were told to respond to the letter and the tone as quickly and accurately as possible.

*Stopping group.* Subjects in the stopping group were first told about the letter task and the responses appropriate to it, and then the stopping task was introduced. They were told to respond to the letters as quickly and accurately as possible but to try to inhibit their responses to the letters if they heard the tone. They were told not to wait for the tone before responding to the letter, that tone delays had been selected in such a way that some of the time they would be able to inhibit their responses to the letter and some of the time they would not.

*Change group.* Subjects in the change group were first told about the letter task and the responses appropriate to it, with encouragement to respond as quickly and accurately as possible. Then they were told to try to inhibit their responses to the letter if they heard the tone but not to wait for the tone before responding to the letter. Finally, they were told to respond overtly to the tone as quickly as possible, whenever it occurred, whether or not they were able to inhibit their response to the letter.

*Tone-only group.* In Experiment 1, twelve subjects served as a single-task control for the dual-task and change groups. They received the same set of stimuli as the other groups (i.e., letters and tones with tone delay and tone probability varied), but they were told to ignore the letters and respond only to the tones, making their responses to the tones as quickly as possible.

## Results and Discussion

### Reaction Time to the Letter

The dual-task and stopping paradigms typically produce different reaction times to the first stimulus, in this case, the

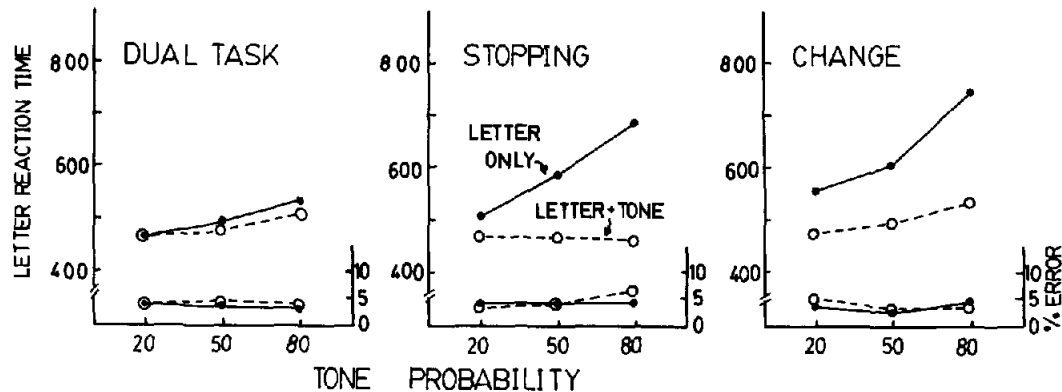


Figure 1. Reaction time (in ms) and error rate for the letter responses on letter-only and letter-plus-tone trials in the dual-task, stopping, and change paradigms of Experiment 1 as a function of tone probability.

letter. In the dual-task paradigm, the response to the second stimulus may interfere with the response to the first, in which case, reaction times should be longer on letter-plus-tone trials than on letter-only trials. In some cases, however, the response to the first stimulus is protected from interference, so there should be no difference between letter-plus-tone and letter-only reaction times; all the interference should appear in reaction times to the tone. By contrast, in the stopping paradigm, letter-plus-tone reaction times are consistently faster than letter-only reaction times (Lappin & Eriksen, 1966; Lisberger, Fuchs, King, & Evinger, 1975; Logan, 1981; Logan et al., 1984). Performance depends on a race between the processes responding to the letter and the processes responding to the stop signal (Logan & Cowan, 1984). A response to the letter occurs only if the letter process is faster than the stopping process; in effect, the stop signal cuts off the slower tail of the distribution of reaction times to the letter. Thus, letter-plus-tone reaction times must be faster than letter-only reaction times because letter-plus-tone reaction times reflect the faster tail of the reaction time distribution, whereas letter-only reaction times reflect the entire distribution, including the slower tail.<sup>1</sup>

*Experiment 1.* Mean reaction times to the letters on letter-only and letter-plus-tone trials are presented in Figure 1 as a function of paradigm and tone probability. The corresponding error rates also appear in the figure. The letter-plus-tone data were collapsed across tone delay because not all subjects responded at each tone delay; the letter-plus-tone data are weighted averages, reflecting the frequency with which responses occurred at each tone delay. The probabilities of responding at each tone delay in each condition are analyzed in the Appendix.

In the dual-task paradigm, letter-plus-tone reaction times were very similar to letter-only reaction times (mean difference = 14 ms), suggesting that subjects protected their responses to the letter, concentrating the interference on the response to the tone. Results like these are often observed in dual-task studies (e.g., Herman & Kantowitz, 1970; Posner & Boies, 1971). In the stopping paradigm, letter-plus-tone reaction times were much faster than letter-only reaction times (mean difference = 134 ms), confirming previous findings (e.g., Lappin &

Eriksen, 1966; Lisberger et al., 1975; Logan et al., 1984) and conforming to the predictions of a race model that assumes independence between the go process and the stopping process (Logan & Cowan, 1984). The change paradigm produced data like the stopping paradigm: Letter-plus-tone reaction times were much faster than letter-only reaction times (mean difference = 132 ms), suggesting that the inhibitory response to the tone cut off the longer tail of the letter-only reaction time distribution.

These effects were confirmed by an analysis of variance (ANOVA) that compared letter-only and letter-plus-tone reaction times in each paradigm and tone probability condition. Overall, letter-plus-tone reaction times were faster than letter-only reaction times,  $F(1, 33) = 29.71, p < .01, MS_e = 13,870.72$ , but the interaction between paradigms and letter-only versus letter-plus-tone was significant,  $F(2, 33) = 5.32, p < .01, MS_e = 13,870.72$ , and planned comparisons revealed significant differences between letter-only and letter-plus-tone reaction times in the stopping paradigm,  $F(1, 33) = 55.13, p < .01$ , and in the change paradigm,  $F(1, 33) = 64.78, p < .01$ , but not in the dual-task paradigm,  $F(1, 33) < 1$ , all  $MS_e = 13,870.72$ . The main effect of paradigms was not significant,  $F(2, 33) = 1.71, MS_e = 67,777.57$ , but the main effect of tone probability

<sup>1</sup> To formalize this prediction, the mean reaction time to the letter, on trials on which subjects failed to inhibit their responses, is

$$\bar{T}_r = \frac{1}{P_r(t_d)} \int_{-\infty}^{t_r+t_d} t f(t) dt,$$

where

$$P_r(t_d) = \int_{-\infty}^{t_r+t_d} f(t) dt$$

equals the probability of responding to the letter, given a stop signal,  $f(t)$  = the distribution of reaction times to the letter on letter-only trials;  $t_r$  = reaction time to the stop signal, which is assumed to be a constant (Logan & Cowan, 1984, demonstrate that this assumption does not seriously affect the predictions in their Appendix);  $t_d$  = delay of the stop signal. According to this equation, the mean letter reaction times on letter-plus-tone trials will increase as  $t_d$  increases, approaching the mean letter-only reaction time in the limit.

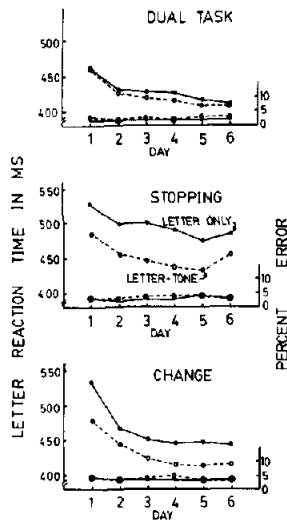


Figure 2. Reaction time and error rate for the letter responses on letter-only and letter-plus-tone trials in the dual-task, stopping, and change paradigms of Experiment 2 as a function of practice.

was significant,  $F(2, 66) = 55.60, p < .01, MS_e = 2,876.24$ , as was the interaction between paradigms and tone probability,  $F(4, 66) = 3.85, p < .01, MS_e = 2,876.24$ ; the interaction between letter-only versus letter-plus-tone and tone probability,  $F(2, 66) = 29.91, p < .01, MS_e = 2,435.86$ ; and the interaction between letter-only versus letter-plus-tone, tone probability, and paradigm,  $F(4, 66) = 3.87, p < .01, MS_e = 2,435.86$ . The effects underlying these interactions were assessed in separate ANOVAs on the letter-only and letter-plus-tone reaction times.

Letter-only reaction times tended to be longer in the stop and change paradigms than in the dual-task paradigm, perhaps because subjects waited for the tone before responding (Logan, 1981; Ollman, 1973). Letter-only reaction times increased as tone probability increased in all three paradigms, but the increase was much stronger in the stop and change paradigms than in the dual-task paradigm. In an ANOVA on the letter-only reaction times, the main effect of paradigms approached significance,  $F(2, 33) = 2.97, p < .07, MS_e = 61,623.27$ , and Fisher's least significant difference (LSD) test revealed a significant difference ( $p < .05$ ) between the dual-task paradigm and the change paradigm and a significant difference between the stopping paradigm and the dual-task paradigm ( $p < .05$ ) but no significant difference between the stopping paradigm and the change paradigm. The main effect of tone probability was significant,  $F(2, 66) = 54.90, p < .01, MS_e = 236,192.00$ , as was the interaction between tone probability and paradigms,  $F(4, 66) = 4.82, p < .01, MS_e = 236,192.00$ .

**Experiment 2.** The mean reaction times from letter-only and letter-plus-tone trials in Experiment 2 are presented in Figure 2 as a function of paradigm and practice. The corresponding error rates also appear in the figure. Again, the letter-plus-tone data were collapsed across tone delay by calculating weighted averages. The probabilities of responding at each tone delay are analyzed in the Appendix.

Again, in the dual-task paradigm, there was very little differ-

ence between letter-only and letter-plus-tone reaction times (mean difference = 9 ms), suggesting that subjects protected their responses to the letter task. There were larger differences between letter-only and letter-plus-tone reaction times in the stopping paradigm (mean difference = 43 ms) and in the change paradigm (mean difference = 33 ms), replicating Experiment 1 and previous research, and confirming the predictions of the race model (Logan & Cowan, 1984).

These effects were analyzed by an ANOVA that compared letter-only and letter-plus-tone reaction times in each paradigm at each day of practice. Overall, letter-only reaction times were faster than letter-plus-tone reaction times,  $F(1, 15) = 29.73, p < .01, MS_e = 1,401.52$ , and the interaction between paradigms and letter-only versus letter-plus-tone was significant,  $F(2, 15) = 3.83, p < .01, MS_e = 1,401.52$ . Planned comparisons revealed significant differences between letter-only and letter-plus-tone reaction times in the stopping paradigm,  $F(1, 15) = 67.97, p < .01$ , and in the change paradigm,  $F(1, 15) = 41.96, p < .01$ , but not in the dual-task paradigm,  $F(1, 15) = 2.47$ , all  $MS_e$ s = 1,401.52. The main effect of paradigms approached significance,  $F(2, 15) = 3.59, p < .06, MS_e = 12,036.73$ , and the main effect of sessions was highly significant,  $F(5, 75) = 14.96, p < .01, MS_e = 1,052.35$ , reflecting a reduction in reaction time with practice in all three paradigms.

As in Experiment 1, a separate ANOVA was performed on the letter-only reaction times, revealing that the main effects of paradigms,  $F(2, 15) = 4.34, p < .05, MS_e = 9,011.20$ , and practice,  $F(5, 75) = 12.39, p < .01, MS_e = 765.65$ , were significant but the interaction between them was not significant,  $F(10, 75) < 1, MS_e = 765.65$ . Fisher's LSD test showed that change-paradigm reaction times were significantly slower than dual-task reaction times ( $p < .05$ ) and stop-paradigm reaction times were significantly slower than change-paradigm reaction times ( $p < .05$ ).

### Overt Reaction Time to the Tone

Reaction times for the overt response to the tone were measured in the dual-task paradigm and in the change paradigm in both experiments and in the tone-only control condition in Experiment 1. On the basis of previous research, we expect dual-task reaction times to the tone to be strongly affected by tone delay, reflecting interference from responding concurrently to the letter (e.g., Kahneman, 1973; Kantowitz, 1974). On the basis of the theoretical analysis in the introduction, we expect change-paradigm tone reaction times to resemble dual-task tone reaction times on signal-respond trials (i.e., when subjects fail to inhibit their responses to the letter). Signal-inhibit trials (i.e., when subjects successfully inhibit their response to the letter) are the most important theoretically: If response competition is the major factor producing dual-task interference, signal-inhibit trials should not produce any interference because only one response is executed; signal-inhibit trials should produce substantially less interference than signal-respond trials. However, if a central bottleneck is the major factor producing dual-task interference, signal-inhibit trials should produce as much interference as signal-respond trials.

**Experiment 1.** Reaction times to the tone in the dual-task

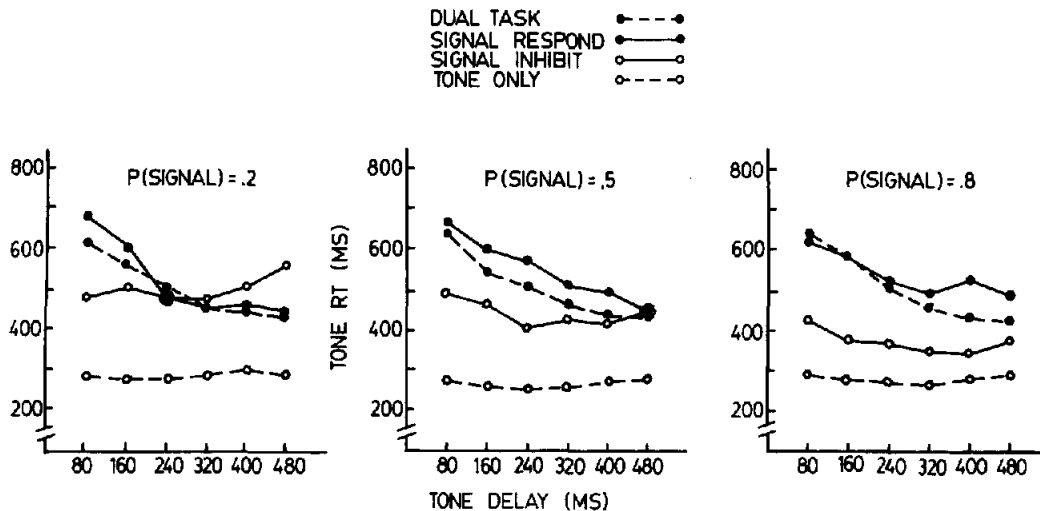


Figure 3. Reaction time (in ms) for the overt response to the tone in the dual-task and change paradigms of Experiment 1 as a function of tone delay and tone probability. (Change data are partitioned according to whether subjects inhibited [signal inhibit] or failed to inhibit [signal respond] the concurrent response to the letter. Tone only data represent single-task controls.)

paradigm and in the tone-only condition are displayed in Figure 3 as a function of tone delay and tone probability. Tone reaction times from the change paradigm are also displayed in Figure 3, partitioned according to whether the concurrent response to the letter was inhibited (*signal-inhibit*) or executed (*signal-respond*).

In the dual-task condition, tone reaction times suffered substantial interference from concurrent responses to the letter. There was a strong effect of tone delay; tone reaction time was much longer at the short tone delays, where there was more overlap between the tone task and the letter task, than at the long delays, where there was less overlap. Moreover, dual-task tone reaction times were substantially longer than single-task tone-only reaction times, even at the longest delay.

The same pattern of interference appeared on *signal-respond* trials in the change paradigm: If subjects failed to inhibit their responses to the letter, tone reaction time was strongly affected by tone delay and was substantially longer than tone-only reaction times, even at the longest delay. Indeed, there was very little difference between *signal-respond* reaction times and dual-task reaction times in any condition. By contrast, reaction times from *signal-inhibit* trials showed very little interference: When subjects succeeded in inhibiting their responses to the letter, tone reaction times were much faster than when they did not (i.e., on *signal-respond* trials and on dual-task trials), and tone reaction times were affected very little by tone delay. *Signal-inhibit* tone reaction times were slower than tone-only reaction times, possibly reflecting a concurrence cost from preparing to respond to the letter (cf. Logan, 1979; Navon & Gopher, 1979), but the difference became smaller as tone probability increased.

We could not use conventional ANOVA techniques to compare *signal-inhibit* and *signal-respond* reaction times from the change task with each other or with reaction times from the dual-task paradigm because of missing observations from sub-

jects who inhibited all the time at short delays or responded all the time at long delays. An ANOVA was conducted to compare the dual-task reaction times with the change reaction times without partitioning them into *signal-inhibit* and *signal-respond* trials. It revealed a significant main effect of tone delay,  $F(5, 110) = 66.18, p < .01, MS_e = 319,072.00$ , and a significant interaction between delay and paradigms,  $F(5, 110) = 19.13, p < .01, MS_e = 319,072.00$ , indicating that the effect of tone delay was weaker in the change paradigm than in the dual-task paradigm because of the mixture of *signal-inhibit* and *signal-respond* trials.

We compared the delay effects in the *signal-respond* and *signal-inhibit* reaction times in the change paradigm by fitting straight lines to the functions relating reaction time to tone delay and performing an ANOVA on the slope values. Altogether, there were four missing observations because of subjects who inhibited at all but two of the delays or responded at all but two of the delays; the missing observations were estimated following the procedure suggested by Winer (1962, pp. 281–283). The ANOVA revealed a significant difference between the *signal-respond* slope ( $-.608$ ) and the *signal-inhibit* slope ( $-.152$ ),  $F(1, 11) = 15.64, p < .01, MS_e = 0.2391$ , and no other significant effects (i.e., no effect of tone probability and no interaction between tone probability and *signal-respond* vs. *signal-inhibit*). The slope in the *signal-inhibit* condition was not significantly different from zero,  $F(1, 11) = 1.74$ .

The pattern of the data is consistent with a response competition interpretation of dual-task interference: The amount of interference observed depended on the amount of competition for access to the response system. When two responses had to be executed in rapid succession (i.e., in the dual-task group and on *signal-respond* trials in the change group), there was substantial interference that diminished as tone delay increased. But when only one response had to be executed (i.e., on *signal-inhibit* tri-

als in the change group), there was very little interference. The lack of interference on signal-inhibit trials suggests that a central bottleneck plays a minor role in the present versions of the dual-task and change paradigms.

*Experiment 2.* The tone reaction times in the dual-task paradigm are displayed in Figure 4 as a function of tone delay and practice. Tone reaction times from the change paradigm are also plotted in the figure, divided into signal-respond and signal-inhibit trials. As in Experiment 1, there was substantial interference in the dual-task paradigm, with tone reaction times strongly affected by tone delay. Also as in Experiment 1, reaction times from signal-respond trials in the change paradigm showed the same interference as the dual-task condition, being strongly affected by tone delay and very similar in magnitude to the dual-task reaction times. Again, the signal-inhibit trials showed a different pattern of performance: Successfully inhibiting the response to the letter eliminated interference, producing reaction times that were not affected much by tone delay and were much faster than signal-respond and dual-task reaction times.

Again, missing observations made it impossible to compare signal-inhibit, signal-respond, and dual-task reaction times with ANOVA. An ANOVA that compared the two paradigms without dividing the change-paradigm data into signal-respond and signal-inhibit conditions yielded a significant main effect of practice,  $F(5, 50) = 13.86, p < .01, MS_e = 7,678.72$ , a significant main effect of delay,  $F(5, 50) = 78.58, p < .01, MS_e = 3,085.76$ , and a significant interaction between delay and paradigms,  $F(5, 50) = 15.98, p < .01, MS_e = 3,085.76$ , reflecting the effects of mixing together signal-respond and signal-inhibit reaction times. Notably, there was no interaction between delay and practice; the delay effect was relatively stable.

Again, we assessed the delay effects in the signal-inhibit and signal-respond conditions by fitting straight lines to the functions relating reaction time to delay and performing an ANOVA on the slopes. The ANOVA revealed a significant difference between the signal-respond slope ( $-.511$ ) and the signal-inhibit slope ( $-.172$ ),  $F(1, 5) = 4.41, p < .05, MS_e = 0.4689$ , and no other significant effects (i.e., no effect of practice and no interaction between practice and signal-respond vs. signal inhibit). The slope in the signal-inhibit condition was not significantly different from zero,  $F(1, 5) = 1.14$ .

As in Experiment 1, the lack of interference on signal-inhibit trials, contrasted with the large amount of interference on signal-respond trials, supports response competition interpretations of dual-task interference (e.g., Herman & Kantowitz, 1970; Keele & Neill, 1978; Reynolds, 1964), and fails to support interpretations based on competition for more central resources (e.g., Kahneman, 1973; Posner & Boies, 1971).

The absence of an interaction between tone delay and sessions is remarkable, because it suggests there was no reduction in dual-task interference with practice. Typically, under consistent mapping conditions there is a substantial reduction in dual-task interference with practice, reflecting the development of automaticity (e.g., Logan, 1979). The present experiment may not have produced a practice effect because the major source of dual-task interference was response competition; subjects had two responses to make on each letter-plus-tone trial, and this

requirement did not change over practice. Possibly, reductions in dual-task interference occur only when subjects can change the way they do the task over practice to eliminate sources of interference. Indeed, Broadbent (1956) found that practice reduced dual-task interference only when subjects did not have to respond to the two tasks simultaneously; practice had no effect on dual-task interference when subjects had to respond to the two tasks simultaneously.

### *Internal Reaction Time to the Stop Signal*

This article is intended to account for the difference in interference between the dual-task and the stop-signal paradigms. The preceding section addressed the interference in the dual-task paradigm; this section addresses the lack of interference in the stop-signal paradigm. The lack of interference is an inference derived from the assumption that the processes responding to the stop signal are independent of the processes responding to the go signal, in this case, the letter. The assumption that the underlying processes are independent has been tested in two ways: First, reaction times to the letter on letter-only trials are typically slower than reaction times to the letter on letter-plus-tone trials, just as we observed here. Logan and Cowan (1984) used their model to estimate letter reaction times on letter-plus-tone trials and found close agreement with the observed values, which supports the independence assumption. Second, estimates of the latency of the internal response to the stop signal derived from the model suggest that reaction times to the stop signal were very fast (about 200 ms) and not affected much by stop-signal delay (see Logan, 1981; Logan & Cowan, 1984; Logan et al., 1984), which supports the independence assumption at least qualitatively. Our purpose here was to test the independence assumption quantitatively in order to provide a more stringent test of the lack of interference in the stop-signal paradigm. First, we used Logan and Cowan's (1984) model to estimate stop-signal reaction time, and then we tested the idea that the effect of stop-signal delay on stop-signal reaction time was due to variability in the stop-signal reaction times, as Logan and Cowan (1984) suggested, by extending their model further.

According to Logan and Cowan's (1984) model, the stop-signal paradigm involves a race between the processes responding to the letter and the processes responding to the stop signal. If the processes responding to the letter win the race, the subject responds to the letter; if the processes responding to the stop signal win the race, the subject inhibits the response to the letter. Letter reaction time and stop-signal reaction time are assumed to be independent random variables, so the race is a stochastic process. The race model is depicted in the top panel of Figure 5, in which there is a distribution of finishing times for the processes responding to the letter and a distribution of finishing times for the processes responding to the stop signal. This version of the model allows us to estimate the mean stop-signal reaction time (see Logan & Cowan, 1984, pp. 311–313), but it does not allow separate estimates at each stop-signal delay, which we need to assess refractoriness in a way that we can compare to the refractoriness of the overt response to the tone.

The model provides another way of estimating stop-signal reaction time if we are willing to assume that the response to the

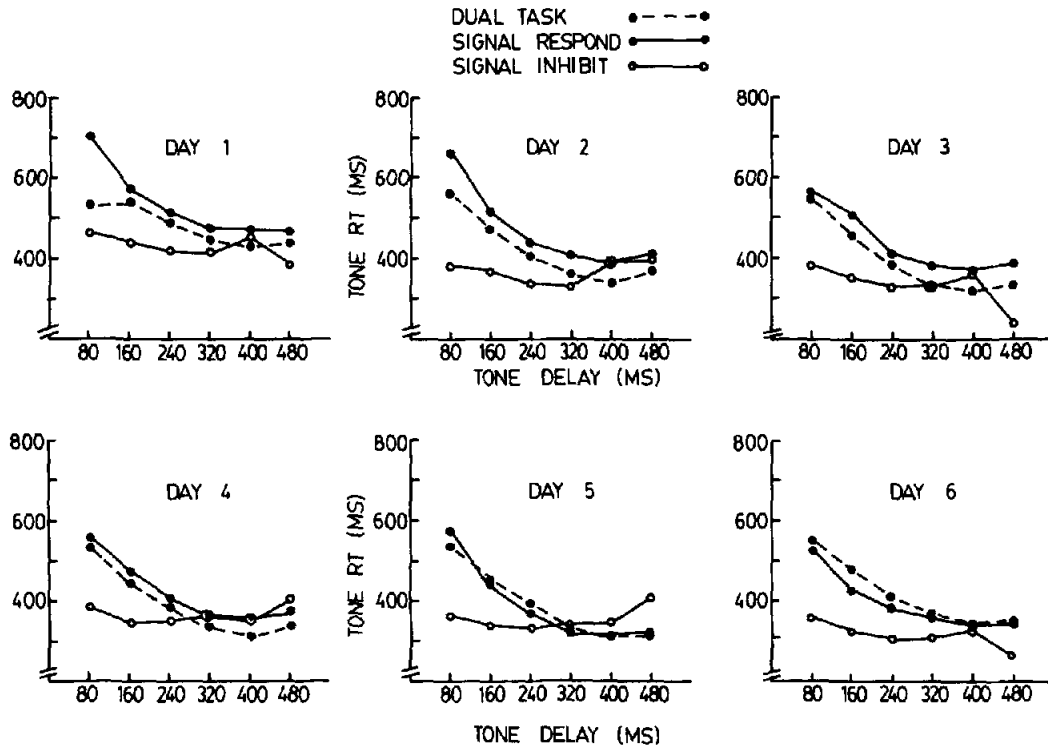


Figure 4. Reaction time (in ms) for the overt response to the tone in the dual-task and change paradigms of Experiment 2 as a function of tone delay and practice. (Change data are partitioned according to whether subjects inhibited [signal inhibit] or failed to inhibit [signal respond] the concurrent response to the letter.)

stop signal is a constant, not a random variable. Stop-signal reaction time is not likely to be constant, but Logan and Cowan (1984, pp. 326–327) showed that assuming it to be constant has a negligible effect on the accuracy of estimation, so the truth of the assumption is of little consequence. The method is illustrated in the second panel of Figure 5, where stop-signal reaction time is represented as a point on the time axis, dividing the letter reaction time distribution into two parts. To the left of the point representing stop-signal reaction time, the processes responding to the letter are faster than the stop-signal processes, and the subject responds; to the right of the point, the stop-signal processes are faster, and the subject inhibits. To estimate stop-signal reaction time, we must determine where that point lies on the time axis and subtract out stop-signal delay. All we need is the distribution of letter reaction times and the probability of responding on letter-plus-tone trials. We integrate the letter reaction time distribution until the integral equals the probability of responding, and read the value of the time axis. This amounts to moving a line from left to right across the distribution in the figure until the area to the left of the line equals the probability of responding, and then reading the value of the time axis at that point.

In practice, we rank-order the letter-only reaction times from fastest to the slowest and select the  $n$ th reaction time as an estimate of the time at which the internal response to the tone occurred, where  $n$  is calculated by multiplying the probability of responding at a given delay by the number of reaction times in

the letter-only distribution. This estimate represents the time at which the response to the tone occurred relative to the onset of the letter. To get an estimate of tone reaction time relative to the onset of the tone, tone delay must be subtracted from this value.

More formally, reaction time to the stop signal,  $t_s$ , can be estimated by finding the point  $r(t_d)$  on the cumulative distribution of letter-only reaction times that corresponds to the probability of responding, given a signal at delay  $t_d$ , and subtracting  $t_d$  from that value. Formally,  $t_s$  is estimated as follows:

$$t_s = r(t_d) - t_d, \quad (1)$$

where  $r(t_d)$  is defined as

$$P_r(t_d) = \int_{-\infty}^{r(t_d)} f(t) dt.$$

$P_r(t_d)$  is the probability of responding given a tone at delay  $t_d$ , and  $f(t)$  is the distribution of reaction times to the letter on letter-only trials.

In Logan and Cowan's (1984) data, estimates of stop-signal reaction time decreased as tone delay increased, mimicking a refractory effect that would occur if the processes were not independent. However, the race model can account for a substantial part of the delay effect if it is assumed that there is some variability in the internal reaction times to the tone: If that were the case, then the effective stop-signal reaction time would decrease as tone delay increased, because only the faster stop-signal re-



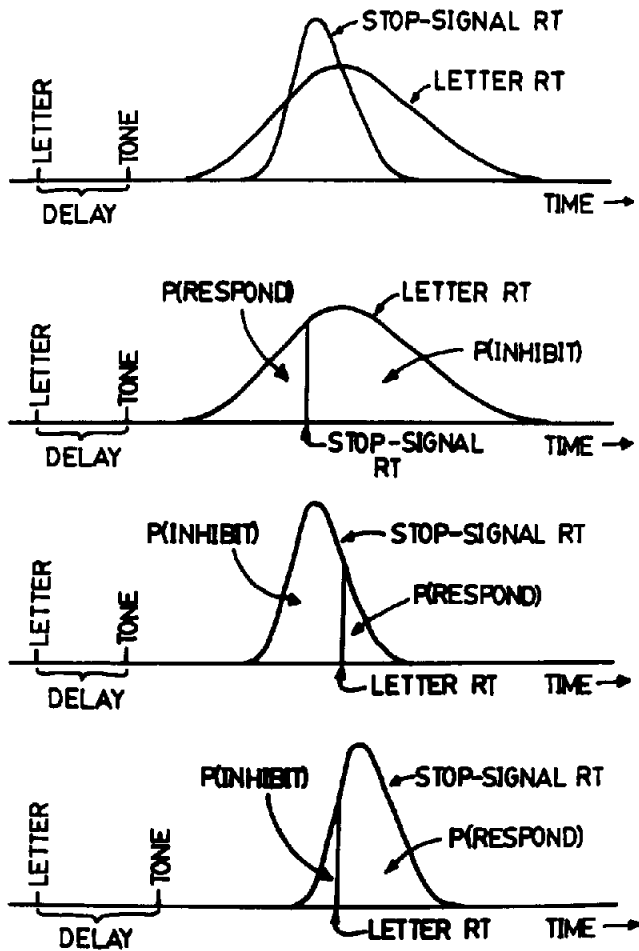


Figure 5. Graphic representation of the horse-race model of response inhibition. (The top panel presents the full model, in which the response to the letter and the response to the stop signal are both random variables. The second panel presents a version of the model in which letter reaction time is a random variable and stop-signal reaction time is a constant, which allows the estimation of stop-signal reaction time [RT] at each tone delay. The third and fourth panels present a version of the model in which stop-signal reaction time is a random variable and letter reaction time is a constant, which allows the estimation of the effects of variability in stop-signal reaction time on the estimates of mean stop-signal reaction time [see text for further explanation].)

sponses would be capable of winning the race at the longer delays. This is illustrated in the bottom two panels of Figure 5, in which stop-signal reaction time is represented as a random variable (i.e., it is distributed across time) and letter reaction time is represented as a constant. In these panels, the area under the stop-signal reaction time distribution to the left of the point representing the (constant) reaction to the letter represents the probability of inhibiting. The effective stop-signal reaction time is the mean of the distribution to the left of that point. The effective stop-signal reaction time is shorter in the bottom panel than in the one above it because tone delay is longer, so the response to the letter cuts off more of the stop-signal reaction time distribution.

More formally, let the mean reaction time to the tone be defined in the following way:

$$\bar{T}_s = \frac{1}{P_s(t_d)} \int_{-\infty}^{t_r - t_d} t f_s(t) dt, \quad (2)$$

where

$$P_s(t_d) = \int_{-\infty}^{t_r - t_d} f_s(t) dt = \int_{t_s + t_d}^{\infty} f(t) dt$$

equals the probability of inhibiting the response to the letter when given a tone at delay  $t_d$ ;  $f_s(t)$  is the distribution of internal reaction times to the tone; and  $t_r$  is the expected reaction time to the letter, which is assumed to be constant for ease of exposition. According to Equation 2, the mean reaction time to the tone will decrease as  $t_d$  increases, even though the processes responding to the tone and the processes responding to the letter are independent.

In order to evaluate this prediction, some assumptions must be made about the form of the distribution  $f_s(t)$ . Then estimates of the observed tone reaction times can be made for each tone delay by calculating the mean of the fast tail of the distribution, using the observed probability of responding, given a tone, to determine where to cut off the tail. We considered two extreme possibilities, the normal distribution and the exponential distribution. For both distributions, some constraints were imposed on the parameter space that was searched to find the best fit. For the normal distribution, the parameter space for the mean ranged from the fastest to the slowest of the observed tone reaction times, because Equation 2 suggests that the mean of  $f_s(t)$  cannot be smaller than the smallest observed value (where  $t_d$  is very long), and it is unlikely to be larger than the largest observed value (where  $t_d$  is very short); the parameter space for the standard deviation ranged from zero to the slowest of the observed tone reaction times. The exponential distribution was not fit by itself because its minimum value is zero, which is not plausible as the shortest tone reaction time. Instead, a constant was added to the exponential in order to produce plausible minimum tone reaction times. The constant was allowed to vary from zero to the shortest observed tone reaction time minus one, and the mean of the exponential was allowed to vary from zero to the longest observed tone reaction time plus 100.

If the stopping process is independent of the processes responding to the letter, then predictions generated from Equation 2 should agree well with the estimated latencies of stop-signal reaction time. If there is substantial disagreement between the predicted values and the estimates, particularly at the short delays, the assumption of independence should be rejected.

*Experiment 1.* Estimates of stop-signal reaction time were calculated for each delay in each condition for each subject in the stop paradigm and the change paradigm, except when a subject responded all the time or inhibited all the time. The means across subjects appear in Figure 6 as a function of tone delay. The three panels on the left contain data from the stop paradigm; the three panels on the right contain data from the change paradigm. Each panel in each paradigm represents a different tone probability condition.

The figure shows that stop-signal reaction times were longer

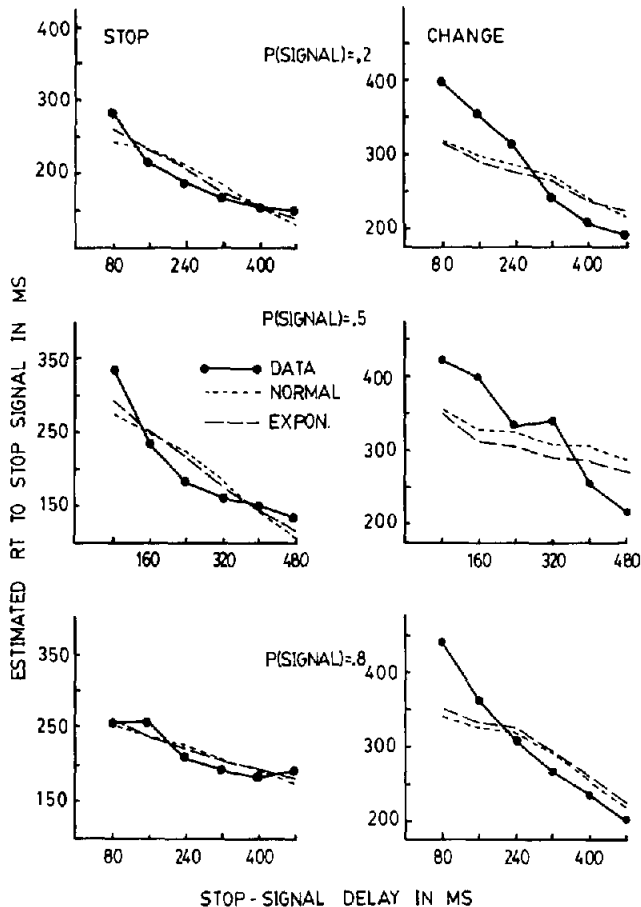


Figure 6. Estimated reaction times for the internal response to the tone in the stop and change paradigms of Experiment 1 as a function of tone delay and tone probability. (Data = the estimated reaction times based on Equation 1. The broken lines represent theoretical predictions, assuming that the distribution of internal reaction times to the tone is normal or exponential [expon.]

in the change paradigm than in the stop paradigm for each tone probability. Averaged across tone probability, the mean stop-signal reaction time was 204 ms in the stop paradigm and 305 ms in the change paradigm. Moreover, in each condition of each paradigm, stop-signal reaction times tended to decrease as tone delay increased, just as the overt responses to the tones increased in the dual-task paradigm. The effects of paradigm and tone probability were assessed by an ANOVA, but it was not possible to assess the effects of delay because of missing observations from subjects who inhibited all the time or responded all the time. Thus, the ANOVA collapsed the data across tone delay. It revealed a significant main effect of paradigms,  $F(1, 22) = 9.31, p < .01, MS_e = 12,996.60$ , but no effect of tone probability,  $F(2, 44) = 1.34, MS_e = 4,789.38$ .

The decrease in stop-signal reaction time as tone delay increased is interesting because it suggests that the internal response to the stop signal may be susceptible to the same refractory effects as the overt responses. Indeed, the slopes in Figure 6 seem about the same as the slopes in Figure 3. Such refractory

effects are important because they suggest that the response to the stop signal and the response to the letter are not independent of each other.

In order to test the assumption of independence, we generated predicted stop-signal reaction times from Equation 2, using the normal and the exponential distribution, and compared the predicted reaction times with the observed values. The best-fitting predictions for each distribution are plotted in Figure 6 along with the observed stop-signal reaction times. The parameters of the best-fitting normal and exponential distributions that were used to generate the predictions appear in Table 1. The two distributions, though very different in shape, generated almost identical predictions. The predictions were much better in the stopping paradigm than in the change paradigm, primarily because of the constraints imposed on the parameter spaces: The best-fitting functions lie outside the constraints more often in the change paradigm than in the stop paradigm. For the normal distribution, the mean reached its maximum for only one condition in the stop paradigm (tone probability = .8), whereas it reached its maximum in all three conditions of the change paradigm. For the exponential distribution, no parameter reached its maximum value in any of the stopping conditions, but the constant reached its maximum value in two of the change conditions (the .2 and .5 tone probabilities).

More important than these discrepancies is the fact that the shape of the predicted functions is different from the shape of the observed functions: For both distributions, the predicted functions tended to be straight or slightly concave downwards, whereas the observed functions tended to be concave upwards. This suggests that although Logan and Cowan's (1984) race model can account for much of the variability in stop-signal reaction time, there may be some other processes involved that also have an influence.

*Experiment 2.* Stop-signal reaction times were estimated at

Table 1  
Parameters (in Milliseconds) of Normal and Exponential Distributions Fit to Estimates of Reaction Time for the Internal Response to the Tone in Experiment 1 as a Function of Paradigm and Tone Probability

Paradigm & tone probability (%)	Normal			Exponential		
	<i>M</i>	<i>SD</i>	<i>RMSD</i>	<i>M</i>	<i>C</i>	<i>RMSD</i>
Stopping						
20	266	93	22	199	121	15
50	303	190	36	310	53	28
80	261	106	16	138	140	15
Change						
20	402	137	47	312	190	51
50	424	122	56	306	218	59
80	439	311	46	498	41	42

Note. *M* = mean of fitted normal or exponential distribution; *SD* = standard deviation of fitted normal distribution; *C* = constant added to exponential distribution to prevent minimum value of zero; *RMSD* = root mean squared deviation between fitted values and estimated values of reaction time for the internal response to the tone.

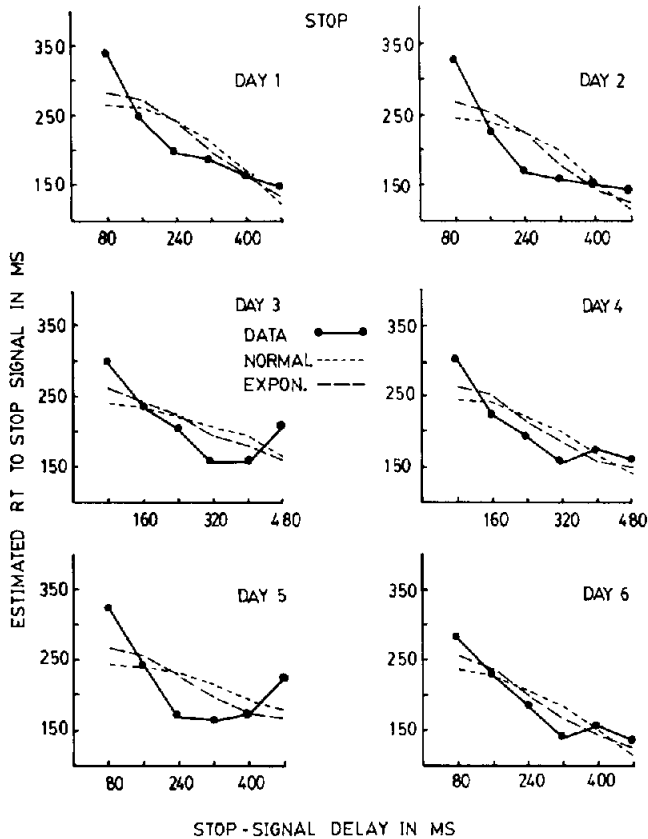


Figure 7. Estimated reaction times for the internal response to the tone in the stop paradigm of Experiment 2 as a function of tone delay and practice. (Data = the estimated reaction times based on Equation 1. The broken lines represent theoretical predictions, assuming that the distribution of internal reaction times to the tone is normal or exponential [expon.] )

each delay for each subject in each condition each day by using the same method as in Experiment 1. The means across subjects in the stop paradigm are displayed in Figure 7, and the means across subjects in the change paradigm are displayed in Figure 8.

Stop-signal reaction times tended to be higher in the change paradigm than in the stop paradigm (averaging 250 ms vs. 206 ms, respectively), and they tended to decrease as tone delay increased in both paradigms. Again, the effects of paradigm and tone probability were assessed by an ANOVA, collapsing the data across tone delay. It revealed a significant main effect of paradigms,  $F(1, 10) = 5.24, p < .05, MS_e = 20,654.65$ ; a significant main effect of sessions,  $F(5, 50) = 3.92, p < .01, MS_e = 894.26$ ; and a marginal interaction between paradigms and sessions,  $F(5, 50) = 2.25, p < .07, MS_e = 894.26$ .

As before, Equation 2 was fit to the data, using the normal and the exponential distribution, and the best-fitting predictions are plotted in Figures 7 and 8 along with the observed tone reaction times. The best-fitting parameters for the normal and exponential distributions that were used to generate the predictions appear in Table 2. This time, the predictions appeared to

be about as good in the change paradigm as they were in the stop paradigm. However, neither of the parameters of the normal distribution reached their limits in the stop paradigm, whereas the mean reached its upper limit on Days 2, 3, and 4 of the change paradigm. For the exponential distribution, the constant reached its limit on one session in the stop paradigm (Day 5), yet it reached its limit on every session in the change paradigm.

Again, the predicted functions were shaped differently from the observed functions, tending to be straight, whereas the observed functions tended to be concave upwards. Though the race model can predict a range of variation in stop-signal reaction time that is about as large as the observed variation, the difference in pattern suggests that the race model may not be the only process contributing to the variation.

### General Discussion

The results of the two experiments were consistent with previous findings in the literature on dual-task and stopping paradigms, demonstrating interference in the former and a general lack of interference in the latter, under identical stimulus condi-

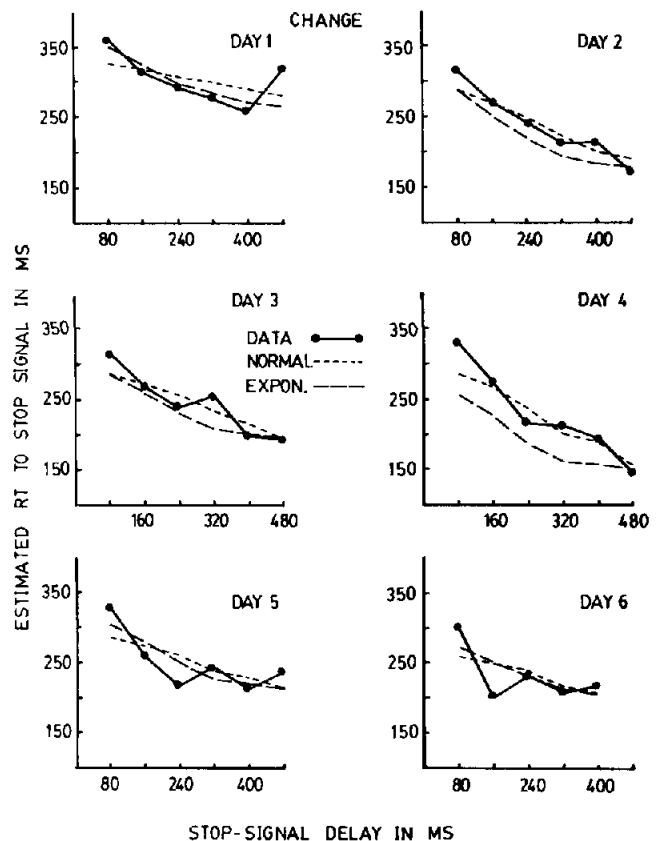


Figure 8. Estimated reaction times for the internal response to the tone in the change paradigm of Experiment 2 as a function of tone delay and practice. (Data = the estimated reaction times based on Equation 1. The broken lines represent theoretical predictions, assuming that the distribution of internal reaction times to the tone is normal or exponential [expon.] )

Table 2  
*Parameters (in Milliseconds) of Normal and Exponential Distributions Fit to Estimates of Reaction Time for the Internal Response to the Tone in Experiment 2 as a Function of Paradigm and Practice*

Paradigm & practice	Normal			Exponential		
	<i>M</i>	<i>SD</i>	<i>RMSD</i>	<i>M</i>	<i>C</i>	<i>RMSD</i>
Stopping						
Day 1	297	113	40	258	114	34
Day 2	264	83	46	215	114	36
Day 3	250	47	40	152	156	31
Day 4	260	64	35	179	141	27
Day 5	255	38	51	161	165	44
Day 6	256	77	28	205	118	18
Change						
Day 1	341	34	27	169	259	24
Day 2	320	66	18	248	172	26
Day 3	318	56	19	226	192	24
Day 4	330	73	22	283	147	47
Day 5	306	42	27	192	214	21
Day 6	274	36	31	144	199	27

Note. *M* = mean of fitted normal or exponential distribution; *SD* = standard deviation of fitted normal distribution; *C* = constant added to exponential distribution to prevent minimum value of zero; *RMSD* = root mean squared deviation between fitted values and estimated values of reaction time for the internal response to the tone.

tions. The results from the change task provide some insight into the different amounts of interference in the dual-task and stopping paradigms, suggesting that response competition was the major source of interference. The evidence supporting these conclusions will be summarized, and some implications will be discussed.

### Dual-Task Paradigm

In the dual-task paradigm, subjects had to complete two responses, and there was substantial interference between them. The shorter the delay between the tone and the letter, the longer the tone reaction times—a finding that reflects the refractory effect observed in many other studies (e.g., Kahneman, 1973; Kantowitz, 1974). The response to the letter was apparently protected from interference, because there was very little difference between letter-plus-tone reaction times and letter-only reaction times.

### Stopping Paradigm

In the stopping paradigm, there was very little evidence of interference between the response to the letter and the (internal) response to the tone (i.e., the stop signal). As predicted by Logan and Cowan's (1984) race model, on the assumption that the response to the letter and the response to the stop signal were independent, letter reaction times for responses that escaped inhibition (signal-respond trials) were considerably faster than letter reaction times from no-signal trials. Moreover, estimates of reaction time to the stop signal were very fast, and most of the

effect of stop-signal delay could be accounted for in terms of variation in stop-signal reaction times, which is consistent with the assumption of independence. However, three effects suggested nonindependence:

First, letter-only reaction times were substantially longer in the stopping paradigm than in the dual-task paradigm, and they were affected much more by tone probability. These effects suggest that the stopping task suffered more interference than the dual task did, but that seems unlikely. For one thing, most theoretical analyses would suggest that the dual task is more demanding, because it involves the production of two motor responses in addition to the stimulus processing that is required for the stopping task. For another, the largest differences between paradigms occurred on letter-only trials, in which there was no other task to produce interference. None of the current interpretations of dual-task interference would predict more interference in single-task (i.e., letter-only) conditions than in dual-task (i.e., letter-plus-tone) conditions (e.g., Kahneman, 1973; Keele & Neill, 1978; Navon & Gopher, 1979; Schweikert & Boggs, 1984; Wickens, 1984).

We suspect that the stop-paradigm letter-only reaction times were slower because subjects waited for the tone before responding. The stopping task and the go task impose opposite demands on the subject—slow responses in the go task increase the probability of stopping, whereas fast responses to the go task decrease the probability of stopping. Thus it would not be surprising if subjects traded speed in the go task for success in the stopping task. Indeed, previous stopping studies indicate that subjects tend to wait for the stop signal (e.g., Lappin & Eriksen, 1966; Ollman, 1973), and they wait longer the higher the probability that the stop signal will occur (Logan, 1981). The large differences in the present study probably reflect the rather high tone probabilities (50%–80%); previous studies used much lower tone probabilities (typically less than 30%).

The second effect that suggested nonindependence was the difference in shape between the stop-signal reaction times predicted from Equation 2 and the "observed" values estimated from Equation 1. The upward concavity in the observed values suggests a refractory effect that could not be accounted for by variance in stop-signal reaction times. However, if a refractory effect occurred, it was rather small, averaging 42 ms in the stopping conditions and 59 ms in the change condition (comparing predicted with observed values at the 80-ms delay in Figures 6, 7, and 8). By contrast, the refractory effect produced by responding overtly to the tone averaged 202 ms, if dual-task reaction times from the shortest delay are compared with reaction times from the longest delay (see Figures 3 and 4), or 341 ms if dual-task reaction times are compared with tone-only (single-task) reaction times at the shortest delay (see Figure 3).

The third effect that suggested nonindependence between the stop and go tasks was the difference in stop-signal reaction times in the stopping and change paradigms; stop-signal reaction times were longer in the change paradigm than in the stopping paradigm in both experiments. The response to the tone was more complex in the change paradigm than in the stopping paradigm, and the difference in complexity may have resulted in more competition for resources between tasks in the change paradigm than in the stopping paradigm. Alternatively, subjects

in the change paradigm may have "grouped" the internal (stopping) and overt responses to the tone, and this may have slowed stop-signal reaction time without demanding more resources. We know very little about factors that affect reaction time to the stop signal; that is an important question for future research.

On the balance, the data do not deviate much from what would be expected if the processes responding to the stop signal were independent of the processes responding to the letter. In the stopping paradigm, at least, the interference between the processes was small, relative to the large amount of interference observed in the dual-task paradigm. One could be impressed by the fact that there was any interference at all in the stopping paradigm, or by the fact that there was substantially more interference in the dual-task paradigm. The latter is what we sought to explain.

### Change Paradigm

The change paradigm was intended to provide some insight into the differences in interference observed in the dual-task and stopping paradigms. When the tone sounded, change-paradigm subjects had to inhibit their response to the letter, like stop-paradigm subjects, and they also had to respond overtly to the tone, like dual-task subjects. The most revealing results were reaction times to the tone partitioned according to whether or not subjects inhibited the response to the letter. When they failed to inhibit the response to the letter (i.e., on signal-respond trials), tone reaction times should suffer interference produced by a central bottleneck as well as interference produced by response competition, resulting from the requirement to make two overt responses. However, when subjects succeeded in inhibiting the response to the letter (i.e., on signal-inhibit trials), tone reaction times should suffer only the interference produced by a central bottleneck; there should be no response competition. By comparing the magnitude of the interference in signal-respond and signal-inhibit conditions, we should be able to assess the relative importance of response competition and central bottlenecks as sources of dual-task interference.

The results of both experiments were very clear: Signal-respond trials produced the same amount of interference as the dual-task trials, whereas signal-inhibit trials produced virtually no interference. This suggests that response competition was the most important source of interference in the dual-task paradigm, and it suggests that central bottlenecks produced very little dual-task interference. It also suggests that differences in response competition are primarily responsible for the large differences in interference observed in dual-task paradigms and stop-signal paradigms.

The point that response competition may produce more interference than competition for central resources was made even more clearly in a change-paradigm study by Logan (1985), in which the primary task was to make category or rhyme judgments about word pairs. As in the present experiments, overt reaction times to the tone were no different from dual-task controls if subjects failed to inhibit their responses to the word pair, but again, like the present experiments, overt reaction times to the tone showed no interference if subjects succeeded in inhibiting their response to the word pair. However, another aspect of

Logan's (1985) experiments suggested that the prereponse processing was the same whether or not subjects inhibited their responses, and thus, whether or not there was interference with the overt response to the tone: The word pairs were presented for a second time in a block in which no tones were presented, and those word pairs whose responses were inhibited on the first presentation produced almost the same benefit from repetition as word pairs whose responses had not been inhibited on the first presentation (also see Logan, 1983, Experiments 3 and 4). Apparently, inhibiting the response did not inhibit the prereponse processing that produced the benefit from repetition. The important point in the present context is that prereponse (i.e., central) processing did not interfere with the overt response to the tone.

The results from the change paradigm also have important implications for studies that use responses to auditory probes to assess the resource demands of visual tasks (e.g., Britton & Tesser, 1982; Posner & Boies, 1971), especially when probe reaction times are compared with control conditions in which there is no overt response to the visual task (e.g., the no-letter "control" of Johnson, Forester, Calderwood, & Weisgerber, 1983, and of Ogden, Martin, & Paap, 1980). The present experiments suggest that those results may reflect response competition more than competition for more central resources, contrary to what the authors of those studies concluded. It would seem prudent to replicate the previous research with some other secondary task and a more appropriate control condition before conclusions about resource demands can be made confidently (cf. McLeod, 1978).

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## Appendix

## Probability of Responding, Given a Signal to Stop or to Change

The probability of responding, given a signal to stop or to change, is not central to the issues discussed in the body of the article, but it determines the number of trials on which signal-respond letter reaction times are based in the stopping and change paradigms, the number of trials on which signal-respond and signal-inhibit tone reaction times are based in the change paradigm, and the estimation of the latency to the internal response to the tone in the stopping and change paradigms. It is presented and analyzed here for completeness.

*Experiment 1.* The mean probabilities of responding, given a tone in the stop and the change paradigms, are presented in Table A1 as a function of tone delay and tone probability. In both paradigms, the probability of responding, given a tone, increased as tone delay increased, replicating typical results in both paradigms (see Logan & Cowan, 1984, for a review), and the probability of responding, given a tone, was higher the lower the tone probability. The effects of tone delay seemed stronger in the stop paradigm than in the change paradigm, and the effects of tone probability seemed stronger in the change paradigm than in the stop paradigm. In particular, the difference between the .8 tone probability and the .5 and .2 tone probabilities was much larger in the change paradigm than in the stop paradigm.

These conclusions were confirmed by an ANOVA on the probabilities of responding given a tone: The main effect of tone delay,  $F(5, 110) = 50.22, p < .01, MS_e = 0.043$ , and tone probability,  $F(2, 44) = 58.95, p < .01, MS_e = 0.042$ , were significant, as were the interactions between paradigms and tone delay,  $F(5, 110) = 5.07, p < .01, MS_e = 0.043$ , between paradigms and tone probability,  $F(2, 44) = 7.23, p < .01, MS_e =$

**Table A1**  
*Probability of Responding, Given a Signal to Stop or to Change in Experiment 1, as a Function of Tone Probability and Tone Delay*

Tone probability	Tone delay (ms)					
	80	160	240	320	400	480
Stopping paradigm						
.20	.12	.23	.34	.56	.72	.83
.50	.08	.17	.25	.40	.54	.64
.80	.03	.13	.19	.30	.42	.52
Change paradigm						
.20	.38	.48	.54	.59	.72	.79
.50	.35	.50	.53	.60	.62	.68
.80	.18	.21	.22	.28	.36	.43

**Table A2**  
*Probability of Responding, Given a Signal to Stop or to Change in Experiment 2, as a Function of Tone Delay and Practice*

Practice session	Tone delay (ms)					
	80	160	240	320	400	480
Stopping paradigm						
1	.16	.18	.28	.48	.68	.85
2	.11	.16	.28	.50	.78	.91
3	.13	.20	.33	.57	.73	.92
4	.14	.18	.38	.59	.84	.93
5	.17	.22	.39	.64	.88	.96
6	.14	.21	.39	.59	.80	.92
Change paradigm						
1	.28	.40	.60	.74	.85	.93
2	.32	.48	.66	.84	.92	.95
3	.38	.52	.70	.88	.93	.97
4	.40	.53	.77	.91	.95	.98
5	.33	.45	.68	.89	.93	.98
6	.28	.44	.70	.89	.95	.96

0.042, and between tone probability and tone delay,  $F(10, 220) = 3.31, p < .01, MS_e = 0.013$ .

*Experiment 2.* The mean probabilities of responding, given a tone in each session, are presented in Table A2 as a function of tone delay and paradigm. As in Experiment 1, the probability of responding, given a tone, increased as tone delay increased, and it was higher in the change paradigm than in the stop paradigm. (Recall that tones occurred on 50% of the trials in Experiment 2 and recall that in Experiment 1 the probability of responding, given a tone, was higher in the change paradigm than in the stop paradigm in the 50% tone condition.)

These effects were confirmed by an ANOVA: The main effect of tone delay was significant,  $F(5, 50) = 74.85, p < .01, MS_e = 0.077$ , and the main effect of paradigms was marginally significant,  $F(1, 10) = 4.24, p < .07, MS_e = 1.182$ . The interaction between delay and paradigms was significant,  $F(5, 50) = 2.89, p < .05, MS_e = 0.077$ , reflecting a ceiling effect at the longer delays. Finally, the main effect of practice was significant,  $F(5, 50) = 3.12, p < .05, MS_e = 0.031$ , though the effects were not very large or obvious.

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