*Research Article*

# Central Interference in Driving

## Is There Any Stopping the Psychological Refractory Period?

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ABSTRACT—*Participants attempted to perform two tasks concurrently during simulated driving. In the choice task, they responded either manually or vocally to the number of times a visual or auditory stimulus occurred; in the braking task, they depressed a brake pedal in response to the lead car's brake lights. The time delay between the onset of the tasks' stimuli, or stimulus onset asynchrony (SOA), was varied. The tasks were differentially affected by the manipulations. Brake reaction times increased as SOA was reduced, showing the psychological refractory period effect, whereas the choice task showed large effects of the stimulus and response modalities but only a small effect of SOA. These results demonstrate that a well-practiced "simple" task such as vehicle braking is subject to dual-task slowing and extend the generality of the central-bottleneck model.*

People's ability—or inability—to perform more than one task at roughly the same time is of substantial interest from both theoretical and applied perspectives of human performance. On a theoretical level, researchers have long sought to characterize human cognitive architecture by uncovering fundamental processing limitations. For practical purposes, an understanding of basic processing limitations should be useful in the optimal design of man-machine systems (e.g., human-computer interfaces, in-vehicle systems).

One potentially important principle of cognitive architecture, often termed the central-bottleneck (CB) hypothesis, was first proposed about half a century ago (Welford, 1952; see Pashler & Johnston, 1998, for a review). According to this hypothesis, certain central mental operations cannot be performed in parallel. These operations are termed "central" because, at least in many laboratory tasks, they occur after ("early") perceptual processing but before ("late") response production. This obligatory serial processing appears to include the selection of responses, but also to encompass other kinds of decision making and memory retrieval (McCann & Johnston, 1992; Pashler & Johnston, 1998). The clearest experimental evidence for this processing bottleneck is found in experiments in which people are instructed to perform two speeded tasks requiring them to respond to two stimuli presented in close temporal proximity, separated by a stimulus onset asynchrony (SOA) that varies from very brief to relatively long (e.g., 50–800 ms). The CB model entails that when central processing is under way for one task, central processing for the other task must be postponed. The model predicts that if subjects carry out the tasks in the same order as the stimuli are presented, then as the SOA decreases, the reaction time (RT) to the second task should increase. This slowing has become known as the psychological refractory period (PRP) effect.

Although many laboratory studies have provided evidence in favor of this model over competing accounts, the occurrence of bottleneck-type delays in real-world activities is far from clear, for two reasons. First, PRP studies usually involve simple and artificial tasks in which only two punctate stimuli are presented, often in a predictable order and separated by an SOA, and a speeded response is made to each. These particular conditions might not reflect those commonly found in the world outside the lab, and it has been suggested that the PRP paradigm may elicit phenomena that would not occur with more naturalistic and continuous kinds of activities. Second, laboratory studies provide far less practice or experience with the tasks than could be obtained by people in real-world settings (e.g., vehicle braking). Even though it has been shown that PRP effects commonly do not disappear with moderate levels of practice (around 36 sessions; see Ruthruff, Johnston, & Van Selst, 2001; Van Selst, Ruthruff, & Johnston, 1999), it is unknown if the effect would occur with real-life activities with which participants have extensive practice (e.g., vehicle braking).

The overall goal of the present study was to determine whether CB phenomena generalize to the real-world activity of driving. To maintain experimental control, we employed a driving simulator, which allowed us to examine the time course of dual-task

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interference between simulated driving and another activity. Many people have logged numerous hours driving a vehicle; indeed, driving experience is usually measured in years, as opposed to hours or even trials, as with typical laboratory tasks. Thus, the simulator allowed us to determine whether a PRP effect can be observed with an extensively performed real-world task. Although a number of studies have shown that concurrent activities cause deterioration in overall driving performance both in the simulator and on the road (Brookhuis, de Vries, & de Waard, 1991; Brown, Tickner, & Simmonds, 1969; Lamble, Kauranen, Laakso, & Summala, 1999; Strayer, Drews, & Johnston, 2003), these studies did not examine the fine-grained time course of such interference.

In the simulator, participants drove along a meandering road using a steering wheel and pedals, following at a close but safe distance behind a lead car that traveled at variable speeds (see Fig. 1). The lead car occasionally braked, thereby requiring participants to depress the brake pedal (hereafter, the *braking task*). In addition, participants performed an intermittent choice response task, in which they indicated with either a manual or a vocal response whether a brief visual or auditory stimulus was presented once or twice. The interference reported in the PRP literature is very similar regardless of the similarity of input and output modalities (Pashler, 1990). We sought to determine whether this would also be the case in the driving environment, which is primarily a visual-manual (and pedal) task. We also varied the SOA between the choice and braking tasks. If the CB model extends to the driving domain, then the braking response would be expected to be slower at short SOAs compared with long ones.

From an applied perspective, understanding task interference affecting the braking task is important because braking is a crucial component of driving. Accident data in the United States reveal that rear-end collisions are a more significant problem than, for example, lane-change collisions, occurring about 5 times as often and resulting in 10 times as many fatalities (Knipling, Wang, & Yin, 1993; Wang & Knipling, 1994).

The braking task, at least to a first approximation, is quite similar to a simple reaction time task (SRT): When the lead car's brake lights illuminate, the only response is to depress the brake pedal; no choice among different response keys is needed. There is some debate about whether a processing bottleneck affects SRTs differently than choice tasks, which are more common in contemporary PRP studies (Karlin & Kastenbaum, 1968; Schubert, 1999; Van Selst & Jolicoeur, 1997). However, the braking task differs from typical laboratory SRTs, in which the effector (e.g., a finger) is resting on the response key and the performer needs simply to issue a "go" command. In driving, the effector (the right foot) is often not resting on the response key (the brake pedal), but is instead "engaging" the gas pedal. Additionally, the driver must typically entertain various considerations when braking (e.g., degree of deceleration; options for slowing, such as active braking or passive deceleration), which likely complicate the decision-making processing. Thus, it would not be surprising from the perspective of CB theory if braking is subject to interference rather similar to that found with choice response tasks.

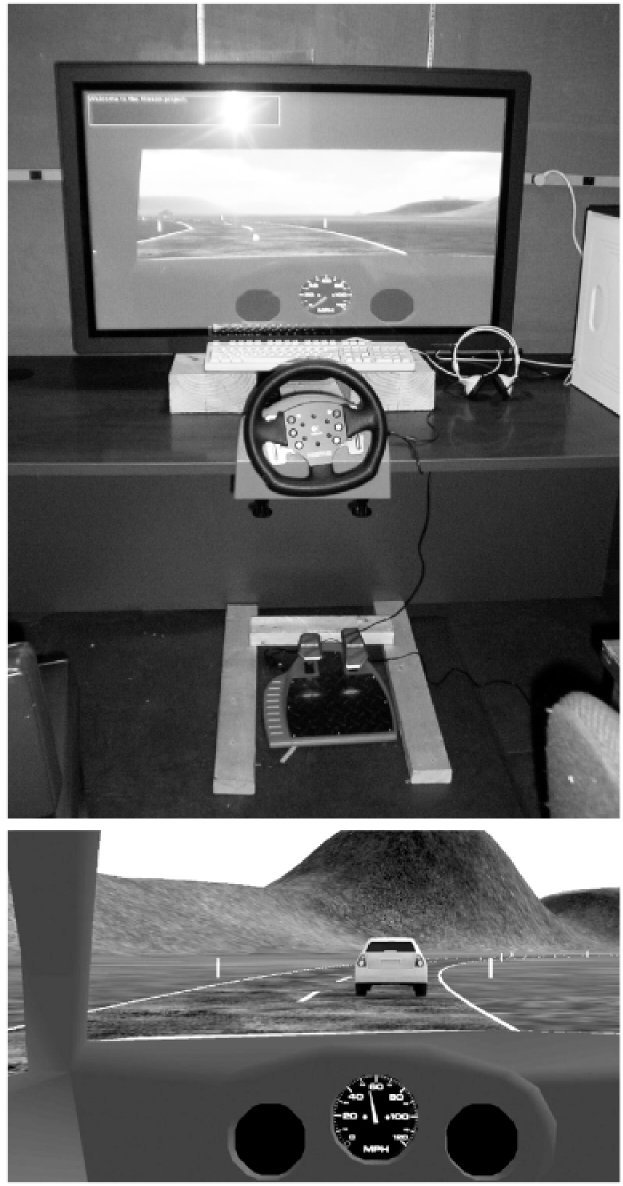

**Fig. 1.** Simulator apparatus (upper panel) and sample screen shot showing the lead car braking (lower panel).

## METHOD

### Participants

Forty students (21 females) at the University of California, San Diego, participated in two 60-min sessions in exchange for partial course credit. The only restriction was that they had at least 2 years of driving experience prior to participation; the average reported length of license ownership was 52.5 months.

### Design

We manipulated three factors, two of which pertained only to the choice task. One was the modality of stimulus presentation;

stimuli were either visual or auditory, with modality randomly determined on each trial but evenly balanced within blocks. The second factor was the modality of response; subjects made either vocal or manual (key-press) responses; response modality alternated between blocks, with the initial response type counterbalanced across subjects. The third factor, manipulated within blocks, was the SOA between the choice and braking tasks on dual-task trials. The four levels were 0, 150, 350, and 1,200 ms, randomly selected on each trial with the restriction that the four levels occurred equally often for each stimulus type within a block.

There were three trial types within all blocks. On the two types of single-task trials, either the choice or the braking task was performed (16 trials each); on dual-task trials, both tasks were performed (8 trials). The 40 trials were presented in random order, and problem trials (e.g., the subject's vehicle lagged too far behind) were rerun later in the block. The intertrial interval (ITI) was an integer randomly selected from 9 through 12 s, inclusive.

### Apparatus and Tasks

The experiment was conducted in a sound-attenuated booth. The medium-fidelity, professionally built driving simulator was written in C++ using the Torque Game Engine and implemented a simplified model of vehicle dynamics. A personal computer (PC) running at 1.47 GHz, allowing for millisecond timing, controlled all aspects of presentation, collection of responses, and recording of data, which occurred every 32 ms. A Hitachi color plasma monitor (model PD1), measuring 106 cm across the diagonal, was situated on a table about 80 cm in front of the seated subject, who wore a standard earphone-microphone headset that was connected to the PC and through which auditory stimuli were presented (including the engine roar of the subject's vehicle, reflecting its speed). Subjects drove the vehicle with a Logitech MOMO Force gaming device, composed of a steering wheel (mounted to the tabletop) and spring-loaded gas and brake pedals (positioned on the floor directly below the tabletop). The response button was located in the inner area of the steering wheel; it could be depressed by the right thumb without removing the hand off the wheel. The gray road was bisected by a dashed white line and had a maximum curvature of 0.01 radians/m. Only the lead vehicle appeared on the road, and it traveled down the right lane at variable speeds, thereby requiring subjects to actively monitor and control their own speed. When the lead car braked, its three brake lights illuminated (see Fig. 1, lower panel). The maximum speed of the lead car was 55 miles/hr (mph), but the maximum speed of the subject's vehicle was 75 mph.

Subjects performed two tasks. One was the braking task: Subjects were instructed to depress the brake pedal with their right foot as soon as they detected the lead car braking. Instructions emphasized that braking (like choice responses) should be prompt, even if an otherwise smoother stop was achievable. The other task was the choice task: A stimulus was presented once or twice (randomly determined), and the task was to indicate the number of occurrences. The auditory stimulus was a tone of 400 Hz presented for 100 ms. The visual stimulus was a change in color of the lead car's rear window: Normally black, the window became white for 100 ms. For twice-presented stimuli, the interstimulus interval was 100 ms. Manual responses were made as single or double key presses on the response button; vocal responses were the words "one" and "two."

### Procedure

The research assistant read aloud the instructions while the subject followed along on a duplicate copy. After the voice-recognition software was trained, the subject familiarized him- or herself with the speed and lateral control of the vehicle. Then he or she performed one practice block of 12 trials under each response modality; all trial types were presented equally often in a random order. Each session included subject-paced rest periods between blocks. The second session (with no practice) was typically run within a few days of the first, but always within 1 week.

## RESULTS

Because sessions were time limited, subjects completed varying numbers of blocks. The data from subjects who completed only a single block in a session were not analyzed ($n = 6$; 4 females); the data of the remaining subjects were collapsed across sessions. Trials on which the brake RT exceeded 3,000 ms or the choice response was incorrect were excluded from RT analyses.

### Choice Task

Percentage correct on the choice task was arcsine-transformed for analysis. There was no significant difference between the single-task (89.8%) and dual-task (89.1%) conditions, as revealed by a one-way analysis of variance (ANOVA), $F(1, 33) < 1$. However, responses to the auditory stimulus (91.2%) were slightly more accurate than responses to the visual one (88.0%), and this difference was significant, $F(1, 33) = 13.90$, $p < .01$. Accuracy was slightly higher with vocal responses (90.9%) than manual ones (88.6%), and this difference was significant, $F(1, 33) = 6.03$, $p < .02$.

Figure 2 presents RTs for the choice task as a function of the stimulus-response factorial combinations. For the single-task condition, the main effects of both stimulus and response modality were significant, $F(1, 33) = 142.99$, $p < .01$, and $F(1, 33) = 67.70$, $p < .01$, respectively, but the interaction was not, $F(1, 33) < 1$. For the dual-task condition, the main effects of both stimulus and response modality were again significant, $F(1, 33) = 140.93$, $p < .01$, and $F(1, 33) = 105.99$, $p < .01$, respectively, as was the interaction, $F(1, 33) = 7.57$, $p < .01$.

In the top panel of Figure 3, RTs for the choice task are presented as a function of SOA for both single- and dual-task

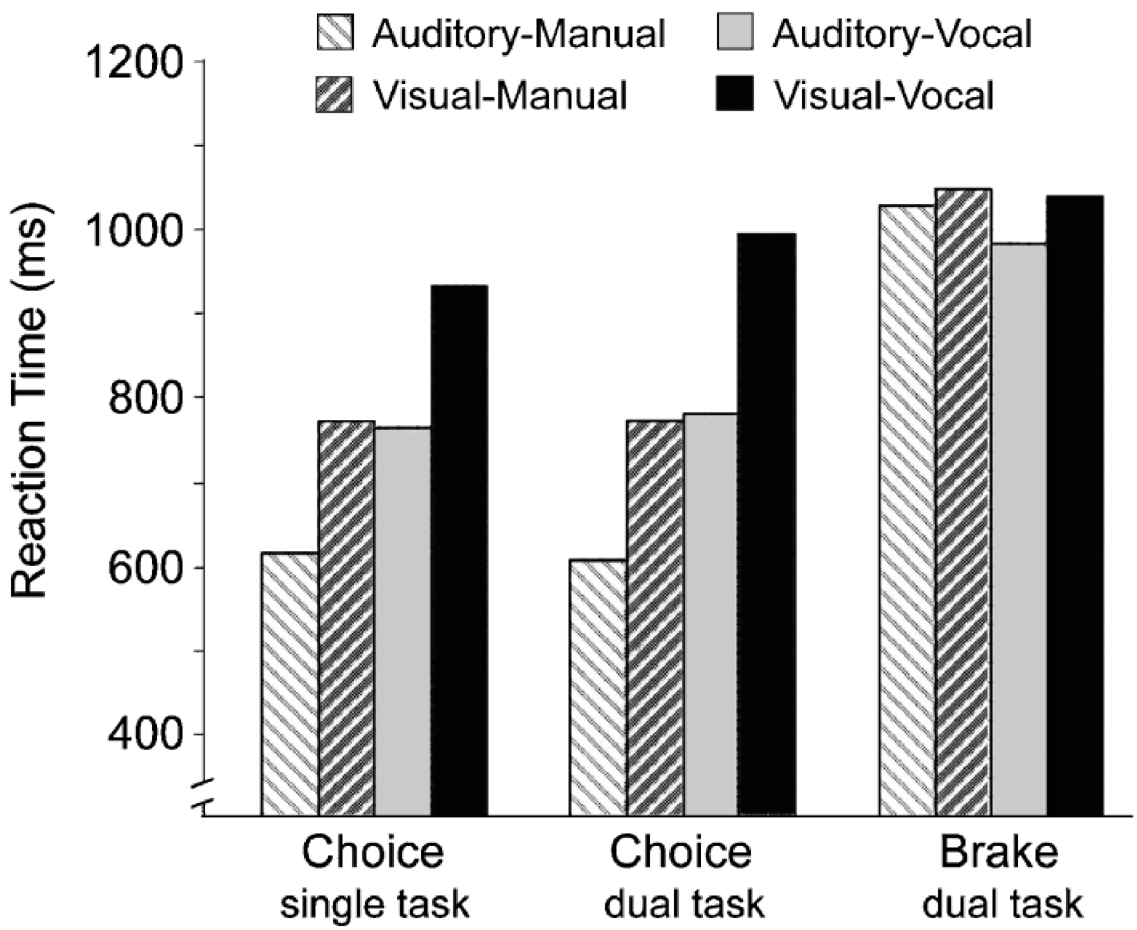


**Fig. 2.** Choice and brake reaction times as a function of the choice task's factorial combinations of stimulus and response modalities. All standard errors of the mean were less than 14 ms.

conditions. Strictly speaking, SOA is a dummy variable when only a single stimulus is presented, but comparing its effects under the two task conditions is illuminating. Not surprisingly, the effect of SOA was not significant for the single-task condition, $F(3, 99) < 1$, although it was significant for the dual-task condition, $F(3, 99) = 3.63$, $p < .02$, $\eta^2 = .05$.

### Braking Task

The brake RT was defined as the interval from the onset of the lead car's brake lights until the initial depression of the brake pedal. In the top panel of Figure 3, brake RTs are plotted as a function of SOA. Not surprisingly, the effect of SOA was not significant for the single-task condition, $F(3, 99) < 1$, although it was significant for the dual-task condition, $F(3, 99) = 23.21$, $p < .01$, $\eta^2 = .33$. We decomposed the brake RTs into two parts: The gas-off RT was defined as the interval from the brake light's illumination until the depression of the gas pedal was less than 20%, and the remaining portion of the brake RT was termed the movement RT. These data are also plotted in the top panel of Figure 3 for the dual-task condition. The effect of SOA was significant both for the gas-off RT, $F(3, 99) = 23.78$, $p < .01$, $\eta^2 = .33$, and for the movement RT, $F(3, 99) = 5.16$, $p < .01$, $\eta^2 = .08$. The brake-RT curve in the dual-task condition contains the hallmark shape of the PRP curve: slowest RT at the shortest SOA (0 ms) with monotonic decrease across the other short SOAs (150 and 350 ms).

The brake RTs in the single-task condition did not differ significantly between vocal-response (966 ms) and manual-response (974 ms) blocks, $F(1, 33) < 1$. The brake RTs in the dual-task condition are presented in Figure 2 as a function of the choice task's stimulus and response modalities. A two-way ANOVA revealed that brake RTs were slightly faster to auditory stimuli than visual ones, $F(1, 33) = 6.96$, $p < .02$, but that neither the response modality nor the interaction of stimulus and response modalities was significant, $F(1, 33) = 2.28$ and $F(1, 33) = 1.73$, respectively.

## DISCUSSION

The most interesting finding from both theoretical and practical perspectives is that the braking response was markedly slowed

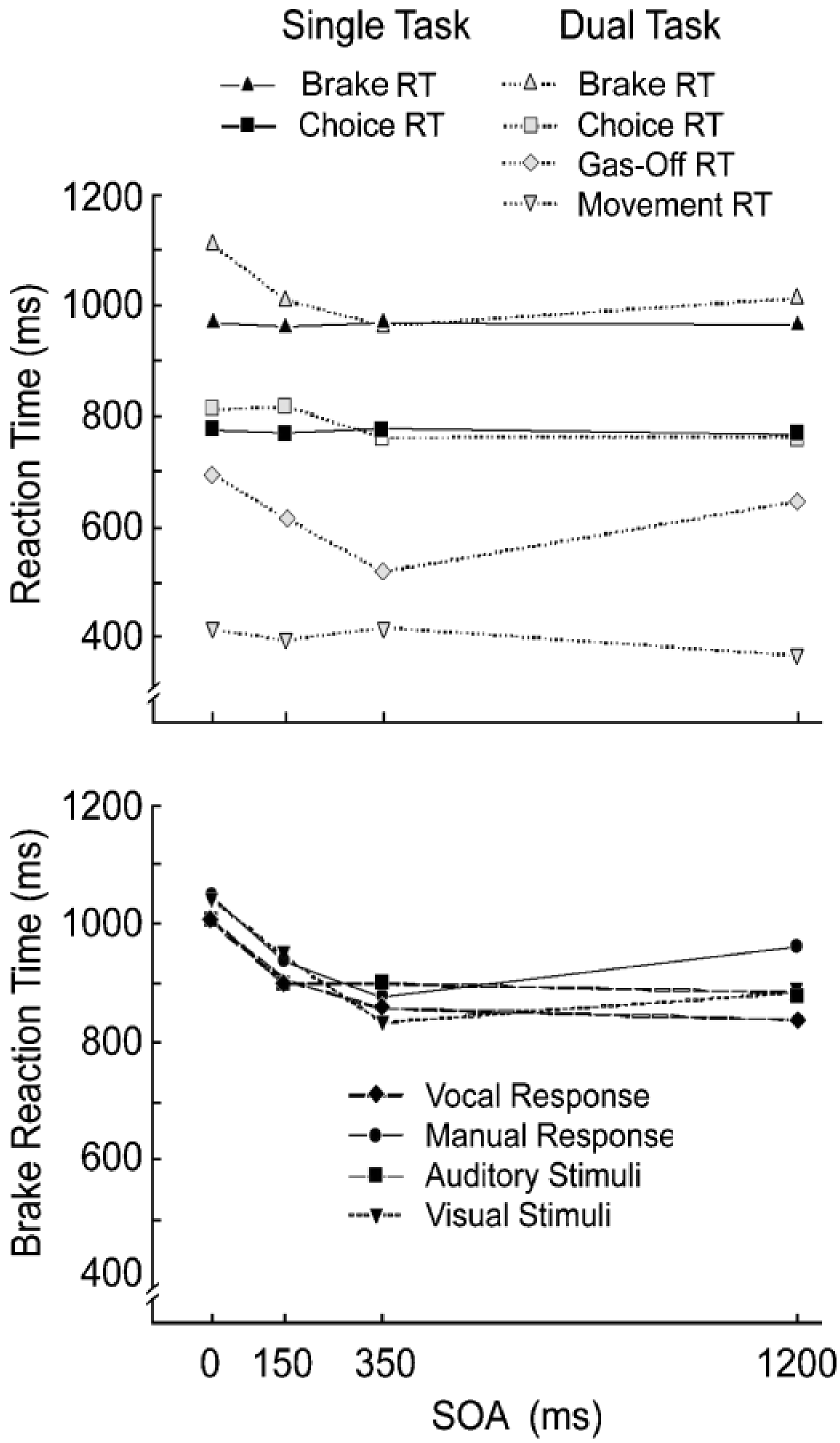


**Fig. 3.** Reaction time (RT) as a function of stimulus onset asynchrony (SOA) in the simulator experiment (upper panel) and the follow-up experiment (bottom panel). In the upper panel, both brake and choice RTs are shown, and brake RTs in the dual-task condition are decomposed into gas-off and movement RTs; all standard errors of the mean were less than 17 ms. In the lower panel, brake RTs are shown as a function of stimulus and response modalities of the choice task; all standard errors were less than 19 ms.

by the concurrent choice task: Brake RTs were slowest at the 0-ms SOA and decreased monotonically over the next two SOA levels. Hence, the prediction of the CB model—the PRP effect—was observed. Thus, even though the choice task was (computationally) easy, responding to the braking task was subject to dual-task interference. This finding is important for several reasons. First, it generalizes PRP slowing to a highly practiced, real-world task (vehicle braking). It appears, then, that vehicle braking is not "automatic," given that performance on another task interferes with it. The effect of SOA on brake RTs (defined as the difference between RTs at the 0-ms and 350-ms SOAs) produced a delay of 174 ms, which has important real-world significance: It translates into more than 16 ft for a vehicle traveling at 65 mph. Indeed, Evans (1991) asserted that "small reductions in reaction time can still reduce the probability and severity of [vehicle] crashes in many cases" (p. 128). Second, this observed slowing demonstrates that the PRP effect can be obtained even with a task that has many characteristics of the laboratory SRT (the decision-making requirements in our braking task were likely simpler than those obtaining for real-world driving, given the instructions emphasizing prompt braking and minimal traffic concerns). Third, the experimental design employed should have discouraged subjects from viewing one task as more important than the other because dual-task trials occurred in only 20% of the block (as opposed to the modal 100%). The remaining 80% of the trials were single-task trials, evenly split between the choice-alone and braking-alone tasks. We used such a low proportion of dual-task trials to discourage subjects from adopting the strategy of "brake as soon as, and only when, the choice stimulus occurs."[1] Thus, the high percentage of braking-alone trials within a block, coupled with the instructions emphasizing fast responses to all tasks, should have discouraged subjects from prioritizing the choice task over the braking task, thereby making it less plausible that the observed dual-task slowing can be attributed to subjects assigning lower processing priority to the braking task.

By decomposing the brake RT on dual-task trials into the gas-off RT and movement RT, one gains further insight into braking behavior. As can be seen in Figure 3, the effect of SOA on the gas-off RT was large (176 ms) and was approximately the same as the effect of SOA on the brake RT (174 ms), whereas the effect of SOA on the movement RT was virtually zero (−3 ms). Similarly, the slopes of the RT curves (computed for the portion of the RT curves from the 0-ms SOA to the 150-ms SOA) were roughly comparable for brake RT (−0.66) and gas-off RT (−0.52), and these slopes were appreciably steeper than that of movement RT (−0.13). These findings imply that the bulk of the dual-task slowing occurred prior to response initiation (moving the foot off the gas pedal) and are similar to the results obtained by Lee, McGehee, Brown, and Reyes (2002), who found in a high-fidelity simulator that rear-end-collision warning systems afforded faster release of the gas pedal than observed when participants drove without a warning system but had no effect on lateral movement times. The delay to initiate movement is, of course, entirely consistent with interference in response planning, not motor control.

Further evidence in favor of the CB interpretation of the slowed braking is the relatively negligible effect of the choice task's stimulus modality on brake RTs. Even though brake RTs on the dual-task trials were faster when an auditory stimulus (1,007 ms) was presented than when a visual stimulus was presented (1,050 ms), the difference was quite small relative to the overall brake RTs. The slight slowing with visual choice stimuli might reflect conflict in (visual) perceptual processing between the stimuli for the two tasks. Alternatively, it might simply be that perceptual processing took longer with visual than auditory stimuli (RTs for the choice task were slower with visual than auditory stimuli in both single- and dual-task trials; see Fig. 2), in which case the CB model would predict that this slowing would propagate onto the braking task (see Pashler, 1994). Thus, these two accounts, which are not mutually exclusive, are both consistent with the CB model.

Additional evidence in favor of central slowing is the lack of effect of response modality on brake RTs, which were not reliably different depending on whether a vocal or manual choice response was made on dual-task trials, or on whether subjects were prepared to respond vocally or manually on single-task trials. Thus, overall, the stimulus and response modalities of the choice task had either little or no effect on performance of the braking task. The lack of such effects is consistent with the view that the between-task interference primarily reflected delays in central processing.

From a practical standpoint, the lack of robust modality effects reinforces the conclusion, derived from more molar driving studies mentioned in the introduction, that performing a concurrent task can seriously impair driving even when the two tasks do not overlap in their sensory or response modalities. Given that driving imposes heavier demands on visual than auditory processing and on manual than vocal processing, one might have expected brake RTs to show a sizable interaction of the choice task's stimulus and response modalities. An interaction was in fact obtained, but its size was notably small compared with the factors' main effects (see Fig. 2). Additionally, RT on the choice task was not greatly affected by the SOA manipulation, and although the slope of the RT curve for this task was reliably greater than zero, it was relatively flat (see Fig. 3, top panel).

One conspicuous aspect of the data is the elevation in the brake-RT curve at the longest SOA in the dual-task condition (the second-task RTs are typically flat across long SOAs in laboratory studies; see Pashler, 1994). In the present study, brake RTs were reliably slower at the 1,200-ms SOA than the 350-ms SOA (Tukey-Kramer multiple-comparison test, $MSE$ = 7,408.477, critical value = 3.695, $\alpha = .05$). A plausible account is that subjects were less prepared to perform the braking task at the 1,200-ms SOA. The elevation at the longest SOA likely reflects two particular experimental characteristics. First, the 1,200-ms SOA was considerably longer than the SOAs typically employed (up to around 800 ms). Second, only 20% of the trials were dual-task trials, and trials were evenly divided among four SOA levels. Hence, given that a choice signal had been

[1]Given the fixed order of stimulus presentation, this would be an effective strategy if only dual-task trials were employed.

presented and the brake stimulus had not yet occurred by 350 ms, the conditional probability that the brake signal would occur was very low (0.111).[2] By contrast, the comparable conditional probability is 1 in typical PRP studies (given 100% dual-task trials within a block). A less-prepared state would likely affect the initiation of the braking response, and indeed gas-off RTs were reliably slower at the 1,200-ms SOA than the 350-ms SOA (Tukey-Kramer multiple-comparison test, $MSE = 7{,}912$, $\alpha = .05$). Subjects may then have attempted to compensate with faster lateral movements, resulting in reliably faster movement RTs at the 1,200-ms SOA than at the 350-ms SOA (Tukey-Kramer multiple-comparison test, $MSE = 3{,}588$, $\alpha = .05$).

We tested the generalizability of our primary finding by conducting a follow-up experiment, which had no driving component but employed the same apparatus and design except that the visual stimulus was a gray rectangle (5.5 cm wide × 4.0 cm high) whose upper half flashed white, and the brake stimulus consisted of a rectangle and two circles, roughly the same size as the brake lights, that were black but became red. Twenty-six new subjects[3] were told to depress the gas pedal except when executing a braking response. Each subject participated in one 60-min session (which began with 10 practice trials per trial type).

The overall results were similar to those obtained in the simulator study, but the most pertinent are brake RTs as a function of SOA, presented in the lower panel of Figure 3 separately for each stimulus modality (collapsed across response type) and response modality (collapsed across stimulus type) of the choice task. A two-way ANOVA revealed that the effect of stimulus modality was not significant, $F(1, 21) < 1$, but the effect of SOA and the interaction of stimulus modality and SOA were significant, $F(3, 63) = 15.76$, $p < .01$, and $F(3, 63) = 4.40$, $p < .01$, respectively. A two-way ANOVA revealed that both response modality and SOA had significant main effects, $F(1, 21) = 8.66$, $p < .01$, and $F(3, 63) = 17.87$, $p < .01$, respectively, and their interaction was significant as well, $F(3, 63) = 2.85$, $p < .04$. The shapes of the RT curves were largely similar to those found in the present simulator experiment and previous PRP studies. We note that there was some elevation at the 1,200-ms SOA for the manual-response condition, which, like the elevation in brake RT at the 1,200-ms SOA in the simulator experiment, might reflect a diminished preparatory state (manual responses were made in about 600 ms).

These results imply that the findings in the present simulator experiment are not unique to the particulars of that study, but rather reflect a basic limit in human information processing. The data clearly demonstrate that performing another task, even a trivial one, can cause substantial slowing in a braking response. If easy tasks affect people's ability to react speedily to braking situations, it seems reasonable to infer that so too would more difficult or engaging tasks that require central operations. Indeed, in a study in which participants performed a pursuit-tracking task, Strayer and Johnston (2001) showed that thumb-press reactions were slower when participants were simultaneously conversing on a telephone than when they were not; interestingly, there was no difference in RTs depending on whether participants used hands-free or handheld phones. This lack of difference converges with our observations involving pedal braking, and further indicates that "freeing up" the hands in a concurrent nondriving task is no guarantee that dual-task interference will be reduced.

[2]This probability was computed as the percentage of dual-task trials with SOAs greater than 350 ms (5%) divided by the sum of the percentage of choice-alone trials (40%) and the percentage of dual-task trials with SOAs above 350 ms (5%).

[3]On average, these subjects had their driver's licenses for 50.5 months. Four subjects completed three or fewer blocks; their data were not analyzed. The ITI ranged from 4 to 7 s.

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