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Task Prioritisation in Multitasking during Driving: Opportunity to Abort a Concurrent Task Does Not Insulate Braking Responses from Dual-Task Slowing

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SUMMARY

In typical dual-task driving studies, participants concurrently perform pairs of driving-related and -unrelated tasks (e.g. vehicle braking and mental arithmetic). Requiring responses to both may implicitly equate their importance. In real-life driving, however, the potential for collision dictates that a concurrent task should be assigned far lower priority than driving. To better reflect naturalistic driving conditions, we not only instructed participants to assign maximum priority to braking in a simulated driving task, but also encouraged them to ignore the concurrent task altogether on dual-task trials. Despite these instructions, responses to the concurrent task often preceded braking, which suffered from dual-task interference. We also found that redundant signals to the lead vehicle's brake lights resulted in faster braking responses and an increased likelihood that the braking response would occur first. The results are consistent with the Central Bottleneck (CB) model of dual-task interference and may help guide the design of driver-assistance systems. Copyright © 2007 John Wiley & Sons, Ltd.

Understanding the human limits of dual-task performance has long been of interest to both basic and applied researchers. From the theoretical perspective, researchers seek to characterise human cognitive architecture at a functional level. Uncovering fundamental processing limitations is obviously a major aspect of that project. From an applied perspective, understanding human limitations as they arise in real-world settings has the potential to enhance interface design and consequently improve safety. Driving is a domain that may particularly benefit from understanding dual-task performance because of the multiple and concurrent demands inherent in the driving task, the fact that events in driving are often time-critical and the frequency with which drivers may attempt to concurrently perform other activities (e.g. conducting a conversation, using in-vehicle devices, etc.).

Brown, Tickner, and Simmonds (1969) examined the effect of reasoning and speaking on perception during driving almost four decades ago, and numerous recent studies have examined the effect of performing other concurrent tasks on driving. The vast majority of dual-task driving studies have required participants to perform both a driving-related and a

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concurrent task, and concurrent performance of another task consistently results in various driving impairments, such as slower braking reaction times (Alm & Nilsson, 1995; Lamble, Kauranen, Laakso, & Summala, 1999; Lee, McGehee, Brown, & Reyes, 2002; Levy, Pashler, & Boer, 2006; Strayer, Drews, & Johnston, 2003), worse steering control (Brookhuis, de Vries, & de Waard, 1991; but see also Kubose, Bock, Dell, Garnsey, Kramer, & Mayhugh, 2005), and less accurate gap judgments (Brown et al., 1969).

Although it is logical in the study of dual-task performance to require responses to both tasks, one inherent limitation of these studies is that they do not accurately reflect real-world driving priorities. That is, participants in these studies may have implicitly assigned equal priority to the tasks because they were required to complete both the driving-related and concurrent tasks. On the road, in contrast, it seems unlikely that anyone would assess a driving-unrelated task (e.g. conducting a conversation) as being as important as, say, applying the brakes in a timely fashion in order to avoid a rear-end collision. After all, a failure to successfully execute the braking response will probably result in damage and possibly injury, whereas failure to contribute to a conversation might at most constitute an annoyance. In order to assess multitasking in the driving context when driving was assigned top priority, we required participants to perform driving-related and -unrelated tasks but explicitly instructed them to assign maximum priority to the vehicle braking whenever both activities were demanded concurrently. To maximise the emphasis on the driving task, we told participants that whenever a braking response was required that a response to the concurrent task was no longer necessary.

The present study was a follow-up to Levy et al. (2006), which employed the overlapping tasks (also known as the psychological refractory period [PRP]) paradigm, often used in the study of dual-task performance; however, the current study utilised the related but less well-known ‘change task’ design (Logan & Burkell, 1986). In the overlapping tasks paradigm, participants on each trial respond to two tasks (Tasks 1 and 2, or T1 and T2), where two stimuli (S1 and S2) are presented and speeded responses are made to both tasks (R1 and R2). The main manipulation is the stimulus onset asynchrony (SOA) which ranges from very brief to relatively long (e.g. 50 milliseconds to 1 second). Typical results are that the reaction time (RT) of T1 (RT1) is unaffected by the SOA manipulation whereas the function relating the RT of T2 (RT2) to SOA has a negative slope that approaches -1 across the range of brief levels (up to around 350 milliseconds) but then flattens out across longer SOAs. This finding, which has been studied for over half a century, is now commonly referred to as the PRP effect. Welford (1952) accounted for the PRP effect by proposing what has come to be known as the Central Bottleneck (CB) model (see Figure 1, upper panel), where central processing (e.g. response selection) is serial: when engaged in processing one task, central processing of another task is postponed (depicted as the filled, B boxes). Other mental events such as ‘early’ (e.g. perceptual analysis) and ‘late’ (e.g. response execution) processing (depicted as boxes A and C, respectively) may proceed in parallel. This model has gained strong support from basic science studies (for reviews, see Pashler, 1994; Pashler & Johnston, 1998), and more recently has been applied to the driving domain (Levy et al., 2006), where the PRP effect was obtained on braking RTs.

In the change task, both S1 and S2 are presented but subjects are told that whenever S2 occurs, they should abort production of R1 and emit only R2. Thus, S2 indicates that participants should ‘change’ from processing T1 to processing T2. Logan and Burkell (1986) demonstrated that participants successfully complied with instructions and withheld making R1 on some trials, whereas on other trials they nonetheless emitted a R1. Thus, it would appear that participants do not have complete control in terminating the

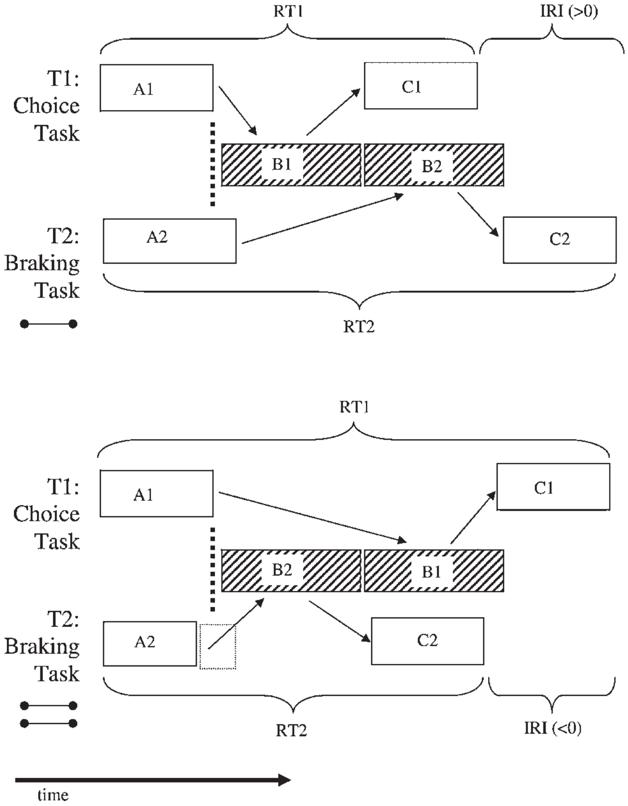

Figure 1. Stage-model diagram illustrating dual-task interference according to the Central Bottleneck theory. Upper panel: Processing for the choice task engages the central mechanism (Box B) first because early processing (Box A1) for this task 'wins the race' (represented by the vertical dashed line) over early processing for the braking task (Box A2), resulting in postponement of the braking-task central processing. The inter-response interval (IRI), defined as RT2–RT1(+SOA), is positive (depicted here is SOA = 0 condition). Single line beneath the braking task label indicates a single braking stimulus. Lower panel: The braking task (with redundant signals, indicated by double lines beneath the braking task label) engages the central mechanism first (Box B) because of faster early processing of the braking task (Box A2) over the choice task (Box A1), resulting in a postponement of the choice task central processing. Dotted box adjacent to A2 represents the putative longer processing time under the single stimulus condition of the upper panel

processing of one task upon presentation of a subsequent signal. Interestingly, RT2 varied strongly by whether or not an R1 was actually produced. When it was, the RT2 curve highly resembled that under the standard PRP design; however, when it was not, the RT2 curve was flat across SOAs. This pattern of data is potentially consistent with the CB model: when R1 is made, central processing was engaged for R1 processing and hence central processing for R2 is delayed, resulting in the PRP effect; when no R1 is made, R2 is not delayed because central processing was not engaged by T1 and so can proceed with processing T2, thereby obviating the effect SOA on R2.

We employed the change task paradigm in the present experiments, conducted in a driving simulator, because this seems to better capture the highly asymmetric importance of driving versus concurrent task productions in the real-world context. However, unlike previous change task experiments, where S1 always preceded S2, we allowed the stimuli

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for the two tasks to appear in either order. There were two reasons for this methodological choice. First, we reasoned that this flexible task order better reflects real-world driving conditions, where driving demands can arise at any time relative to concurrent activities the driver might undertake. Second, because we aimed at stressing the high priority of the braking task, we wanted to avoid even the potential of subtly conveying on dual-task trials that the choice task should be viewed as more important than the braking task. Some have commented that if one task's stimulus always precedes the others, it may be natural to view the former task as meriting higher priority than the latter task.

We further added to the experimental paradigm the manipulation of a redundant signal to the high priority stimulus: simultaneously with the lead car's brake lights, we presented a cross-modal stimulus: a tactor in Experiment 1 and the sound of screeching tyres in Experiment 2. Previous studies have shown faster RTs with redundant signals than just a single stimulus, termed the redundant signals effect (RSE), in both laboratory studies on focused attention (Cavina-Pratesi, Bricolo, Prior, & Marzi, 2001; Miller, 1982, 1991; Mordkoff, Miller, & Roch, 1996) and applied settings with divided attention (Belz, Robinson, & Casali, 1999; Graham, 1999; Sklar & Sarter, 1999).

The combination of redundant signal, flexible task order and high priority of one task over the other allows us to explore a fundamental question relating to the CB model that has received little discussion in the literature: what determines order of access to central processing? If one task's stimulus always precedes the other task's stimulus (particularly with a sizable onset advantage) and performers aim to respond to all tasks as quickly as possible, it seems reasonable that processing pertaining to S1 will likely engage the central processor prior to that pertaining to S2. What is less clear is when experimental conditions—influenced by task priority, 'change' instructions, and the incentive to avoid undesirable consequences—induce the performer to respond quickly to one task over another. Data from Logan and Burkell (1986) imply that under laboratory conditions participants were not entirely successful in withholding a R1 and consequently R2 suffered from dual-task slowing. One purpose of employing a driving simulator was to augment the 'natural' incentive (i.e. fear of collision) to avoid responding to the concurrent task and respond instead to the braking task. Taken together, the above factors potentially allow for what we term the 'race to the bottleneck': when participants are induced to produce speeded responses to tasks and the two stimuli are presented in close temporal proximity, we propose there is a 'race' in early processing between the tasks. The 'winner' of this race gains first access to the serial central processor and consequently central processing for the 'losing' task is postponed. This description therefore predicts that the winning task's RT will be faster than the losing task's by a sizeable amount because central processing is thought to be a sizable portion of the overall RT.[1] Hence, for any trial where both responses are made, the RT to one task should be relatively fast while the RT to the other task should be relatively slow. As a result, the time interval between when the two responses were made, known as the inter-response interval (IRI), should be sizable. This model also predicts sizeable differences in RTs within each task, depending on whether the task won or lost the race. For example, braking RTs should be faster when the braking task wins the race than when it loses. Thus, this model predicts that RTs are contingent on a race and that comparisons can be made both between tasks and within tasks.

If the redundant signal results in a speed-up of processing to the braking task, then this should affect braking RTs in both the single- and dual-task conditions. In single-task

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[1] This also assumes the output of the two responses is not made as a couplet—see Borger (1963).

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conditions, this obviously predicts that braking RTs should be faster with the redundant signal than without. The dual-task condition provides the opportunity to test a more interesting prediction: the redundant signal should lead to an increased probability that the braking task will win the race. Figure 1 should help elucidate this point. The upper panel depicts the condition with only a single braking stimulus (represented by the single line underneath the braking task label). Here, the early processing for the braking task (Box A2) takes more time than that for the choice task, so the braking task 'loses' the race (represented by the vertical dashed line) to the central processor (Box B). As a result of losing the race to the central processor, processing of the braking task is postponed and therefore its RT is relatively long. Further, the IRI[2] should be positive. The lower panel depicts the redundant signal condition (represented by the two lines underneath the braking task label), and due to the RSE, early processing pertaining to the braking task wins the race. As a result of winning the race, processing of the braking task is not postponed and therefore its RT is relatively fast. Therefore, the 'race to the bottleneck' notion coupled with the redundant signal predicts that the presence of the redundant signal should increase the likelihood that braking responses win the race. Additionally, the IRI should be negative.

Intuitively, it is clear that the likelihood of a particular task winning the race should also be affected by the SOA. Under conditions where speeded responses are required, it seems obvious that the earlier presentation of a task's stimulus(i) should lead to an increased probability of that task winning the race compared to a delayed presentation. Therefore, the likelihood of braking responses winning the race should be highest when the braking signal precedes the choice signal. Further, the effect of SOA and redundant signal should combine to affect the likelihoods of winning the race. In other words, the highest likelihood of the braking task winning the race should be when the braking signal, coupled with the redundant signal, are presented before the choice signal.

In the present studies, participants followed a lead vehicle and performed two tasks. One was the *choice task*, wherein participants judged whether a beep occurred once or twice and responded appropriately. In the other task, the *braking task*, drivers depressed the brake pedal as quickly as possible in response to the lead vehicle's brake lights. The brake lights, which served as the 'change' stimulus, also signalled that a response to the choice task should be withheld. Instructions required that responses should be made quickly and accurately but emphasised higher priority of the braking task over the choice task; in fact, participants were instructed that a response to the choice task could be ignored altogether. This design allows us to examine how well drivers can abort processing one task (choice task) in favour of the high priority one (braking). One might suspect that the desire to avoid rear-end collisions should provide enough incentive for drivers to disengage processing the choice task in favour of the braking task. On some braking trials, the braking lights were supplemented by a redundant signal, presented simultaneously with the lights.

EXPERIMENT 1

We manipulated two variables. One was the SOA: either task's stimulus could precede the other task's stimulus. In a third condition, the two tasks' stimuli were presented simultaneously. The other factor was the redundant signal to the brake lights: a vibrating tactor was simultaneously presented on some trials.

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[2] IRI = braking RT + SOA—choice RT.

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Method

Participants

Forty students at the University of California, San Diego, participated in two 1-hour sessions in exchange for partial course credit. The only restriction was that performers had at least 2 years of driving experience prior to participation. The average license ownership was 50.4 months.

Apparatus and the simulator

The experiment was conducted in a private room where individual participants were tested. The driving programme was professionally built and written in C++ using the Torque Game Engine. A personal computer (PC) controlled all aspects of presentation, collection of responses and saving of data, and a Hitachi PD1 colour plasma monitor (with 106 cm diagonal), stationed on a desktop about 80 cm in front of the seated subject, displayed the visual environment. The participant controlled his or her own vehicle with a commercial gaming device (Logitech MOMO force), consisting of a steering wheel mounted to the desktop and spring-loaded accelerator and brake pedals positioned on the floor. The response button was located 5 cm to the left of the steering wheel's 3 o'clock position, allowing right-hand thumb depressions without removing the hand off the wheel. The participant wore a standard headset that was connected to the PC and through which he or she heard the sound of the engine and the tone stimulus. It was a beep of 400 Hz lasting 100 milliseconds; when presented twice on a trial, there was an inter-stimulus interval of 100 milliseconds. A tactor (V1242, Audiological Engineering Corp., Somerville, Mass, USA), a vibrating device with a diameter of 2 cm, was connected to the PC and attached to the driver's left-hand fifth finger[3] with a Velcro band and was driven by a sound file, whose onset was synchronous with the brake light's onset and lasted 400 milliseconds.

Design

We manipulated two factors. One, termed the redundant signal, was whether or not a redundant signal (the tactor) was presented simultaneously with the onset of the lead vehicle's brake lights, and we refer to these two levels as 'lights + tactor' and 'lights-only'. The other factor, SOA, had three levels: the tone preceded the brake signal(s) by 150 milliseconds[4] (termed $\mathrm{SOA}_{150\ \mathrm{tone\ first}}$); the brake signal(s) preceded the tone by 150 milliseconds (termed $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$); or the choice and brake signal(s) were presented simultaneously (termed SOA_0).

There were three trial types within all blocks. On the two single-task trials, participants performed either the choice (36 trials) or braking task (16 trials, evenly divided between the two levels of redundant signal).[5] On dual-task trials (36 trials), both stimuli were presented;

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[3] The purpose of employing a tactor was the abstract goal of providing a redundant signal in a non-visual modality, and so we chose to attach the device to the driver's finger, a convenient location and modelled after Sklar and Sarter (1999). Our goal was not to test the effectiveness of presenting tactors to various locations on the driver's body.

[4] This level of SOA, often used in PRP studies, allows for the interesting possibility that S2 will win the 'race to the bottleneck'. Longer SOAs would likely decrease this possibility given that participants strove to make speeded responses.

[5] Priority to the braking task was induced by stressing its importance, instructions to abort concurrent processing of the choice task and the 'unpleasant' consequences of slow braking responses (i.e. rear-end collisions). But because we also needed to promote ongoing engagement in the choice task in order to test the notion of 'race to the bottleneck' and the aborting of (choice) task processing, we opted to present more choice- than braking-task trials on single-task trials. We note that the greater frequency on single-task trials of one task need not necessarily convey its higher priority. Conversely, we note that on dual-task trials each task's stimulus occurred first equally often.

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the SOA and redundant signal factors were fully crossed (3 × 2) and evenly presented, resulting in six trials of each factorial combination. Thus, a block contained 88 trials, and trial types were presented in random order. Inter-block rest periods were participant-paced.[6]

In following the lead car, participants were instructed and required to maintain a safe but close following distance. If they trailed too far behind the lead vehicle, the trial was interrupted and the inter-car position was reset; if they failed to brake in time, there was a collision.[7] These conditions required participants to find and maintain a reasonable following distance. In the braking task, participants were asked to depress the brake pedal as quickly as possible with their right foot, even if an otherwise smooth stop was possible. The choice task required participants to determine whether a tone was presented once or twice. They responded with single or double thumb presses, respectively, on the response button.

Procedure

The subject was seated within comfortable reach of the steering wheel and pedals. The research assistant read aloud the instructions while the subject followed along on a duplicate copy. Participants were instructed to make the braking and choice responses as quickly and accurately as possible. Not only was it emphasised that braking responses should be prompt (as opposed to gradual deceleration, as is sometimes possible under real-world driving conditions), but the higher priority of the braking response was emphasised:

> ‘Occasionally . . . the lead car will brake right around the time the beeps occur. When this happens, you should give high priority to the braking task. That is, you should not even bother to make the response to the tone task but instead make every effort to step on the brakes as fast as possible. In other words, you should abort carrying out the tone task and step on the brakes. Thus, we are asking you to drive in the simulator as you would in real-life (i.e. avoid rear-ending the lead car)’.

Participants next practiced driving to become familiar with the steering and pedals, and then practiced driving combined with the choice task. Practice was participant-paced but typically lasted around 10 minutes (these data were not analysed). The remainder of the session was devoted to testing. Participants returned for the second session typically within a few days but always within 1 week, and this session was devoted exclusively to testing.[8]

RESULTS AND DISCUSSION

The data from the two test sessions were combined. Trials where the braking RT was faster than 300 milliseconds or slower than 3000 milliseconds were excluded from analysis.

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[6] Thus, all blocks contained the same number of trials (88) and sessions were time-limited (1 hour each). However, the total number of blocks completed varied by participants, depending on how much practice they elected, how long it took to complete each block (e.g. after a collision, trials were re-run) and the duration of the rest periods. Because all factors were manipulated as within-block variables, the varying number of completed blocks should have no systematic effect on the results.

[7] When either outcome occurred, the trial type was randomly re-run later in the block.

[8] Whereas the steering dynamics in the simulator likely differed to some degree for drivers from their experience with their own cars, depressing the brake pedal was probably very comparable to their previous experience. And because the braking response (not steering performance) was analysed here, extensive practice was not needed.

Additionally, we considered only trials where the choice response was correct for the RT analyses.

Choice response made

We first examined the extent to which participants omitted making a response to the choice task on dual-task trials (as the instructions instructed them to do). We computed the percentage of trials for each SOA level where the choice response was made. Natural breaks in the distribution led us to bin the participants into three groups.[9] They were the over 80% ($n = 24$, or 60% of all participants), hereafter termed *high-responders*; between 40–80% ($n = 8$, or 20%), hereafter termed *mid-responders*; and under 40% ($n = 8$, or 20%), hereafter termed *low-responders*. Thus, participants clearly differed in likelihood of aborting the choice task response, although it is not clear why performance differed so drastically among participants on this measure. Below we compare the three-responder groups on single-task performance; for dual-task performance, our analyses are limited to examining only the high-responder group because the other responder groups did not have sufficient observations for meaningful comparisons.

Single-task performance

We compared single-task performance among the three-responder groups. The braking RTs under the lights + tactor and lights-only conditions were: 850 and 925 (SE = 10.5) milliseconds for the high-responders; 824 and 873 (SE = 17.7) milliseconds for the mid-responders; and 895 and 935 (SE = 10.6) milliseconds for the low-responders, respectively. A two-way analysis of variance (ANOVA) revealed a main effect for the redundant signal, $F(1, 37) = 20.20, p < 0.01$, but neither the main effect of responder group nor the interaction was significant, $F(2, 37) < 1$, and $F(2, 37) = 1.03$, respectively.

For the choice task, there was no difference in accuracy or choice RTs among the three-responder groups. The choice RTs (with standard error) were 625 (21), 650 (21) and 669 (37) milliseconds for the high-, mid-, and low-responders, respectively, and a one-way ANOVA revealed no significant differences, $F(2, 37) < 1$. The per cent correct scores (with standard error) were 93.1 (0.02), 91.5 (0.03) and 89.1 (0.03) for the high-, mid-, and low-responders, respectively, and a one-way ANOVA revealed no significant differences, $F(2, 37) < 1$. Thus, the responder groups did not differ in performance for either task under single-task conditions. Further, the lights + tactor condition led to faster braking RTs compared to the light-only condition for all three groups. Thus, other than the defining group variable (ability to withhold making a choice response), there were no differences among the groups.

Dual-task performance

On each dual-task trial where both the braking and choice responses were made, we determined for the high-responder group which response was emitted first (hereafter referred to as First Response) for the factorial combinations of SOA and redundant signal. The per cent (with standard error) of these trials where braking was the First Response were

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[9] The natural breaks likely imply that participants performed the dual-task trials differently. However, as the reader will soon learn, there were no group differences in single-task performance.

as follows for the $\text{SOA}_{-150\text{ brake first}}$, SOA_0 and $\text{SOA}_{150\text{ tone first}}$: with the redundant signal, 51.0 (1.6), 38.7 (1.6) and 23.1 (1.6), respectively; without the redundant signal, 46.4 (1.6), 35.1 (1.6) and 18.6 (1.6), respectively. Both main effects were significant, $F(1, 23) = 7.21$, $p < 0.01$, for redundant signal, and $F(2, 46) = 57.82$, $p < 0.01$, for SOA, although the interaction was not, $F(2, 46) < 1$.

The two main effects support our notion of a race to the bottleneck. First, consider the effect of SOA. The likelihood that a braking response preceded a choice response was highest when the braking signal preceded the choice signal (i.e. $\text{SOA}_{-150\text{ brake first}}$) and lowest in the opposite condition (i.e. $\text{SOA}_{150\text{ choice first}}$). That is, giving the braking signal a ‘head start’ of 150 milliseconds resulted in the highest likelihood that the First Response would be to that signal, and delaying it by 150 milliseconds resulted in the lowest likelihood. This makes intuitive sense where speeded responses are made. Second, the main effect of the redundant signal shows that across all levels of SOA, adding a redundant signal to the brake lights resulted in an increased likelihood of the braking response preceding the choice one. This is consistent with the notion that the redundant signal affords faster processing, and therefore contributes to an increased likelihood that this task will win the race.

We next analysed the RT data for both tasks, separately by First Response,[10] and present the data in Figure 2. We tested the effects of SOA and Response Order,[11] that is, whether the response for each task was emitted as the First or Second Response. As is plainly clear from the figure, each dependent variable was faster when it was the First Response than the Second Response. For choice RTs, both the effects of SOA and Response Order were significant, $F(2, 42) = 12.36$, $p < 0.01$, and $F(1, 21) = 105.76$, $p < 0.01$, respectively; so too was the interaction, $F(2, 42) = 4.25$, $p < 0.02$. For braking RTs, both the effects of SOA and Response Order were significant, $F(2, 42) = 36.15$, $p < 0.01$, and $F(1, 21) = 78.53$, $p < 0.01$; the interaction, however, was not significant, $F(2, 42) = 1.83$. Thus, each dependent measure was relatively fast when it served as the First Response and relatively slow when it served as the Second Response. This within-task comparison (First vs. Second Response) is consistent with the ‘race to the bottleneck’ hypothesis.

The main effect of SOA for each dependent measure resulted in a monotonic slope across the three levels of SOA: the slope was positive for the choice RT curves and negative for the braking RT curves. It might seem odd at first blush that braking RTs were *slower* at $\text{SOA}_{-150\text{ brake first}}$ (where the braking signal preceded the tone one) than at $\text{SOA}_{150\text{ tone first}}$, and conversely that choice RTs were slower at $\text{SOA}_{150\text{ tone first}}$ than $\text{SOA}_{-150\text{ brake first}}$. Should not braking RTs, for example, be *faster* when the braking signal has a ‘head start’, if indeed there is a race? We must remember, however, that these data were partitioned not only by the experimental factor of SOA, but also by the participants’ actual performance, namely, by which response happened to be emitted first on each trial. Hence, there is a selection bias as to how the trials were binned. Consider the case where the braking response was emitted as the First Response in the $\text{SOA}_{150\text{ tone first}}$ condition. Given the stochastic nature of RTs, only braking responses that were relatively fast (or conversely, choice responses that were relatively slow) would be partitioned into this bin, given the head start afforded to the choice task. In contrast, the selection pressure for braking responses to be included in the $\text{SOA}_{-150\text{ brake first}}$ is less, and so some slower braking RTs

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[10] The analyses only considered participants who had observations in all cells.

[11] We attempted adding the effect of redundant signal to the analysis but this resulted in too few data in some cells to allow for reliable inferences.

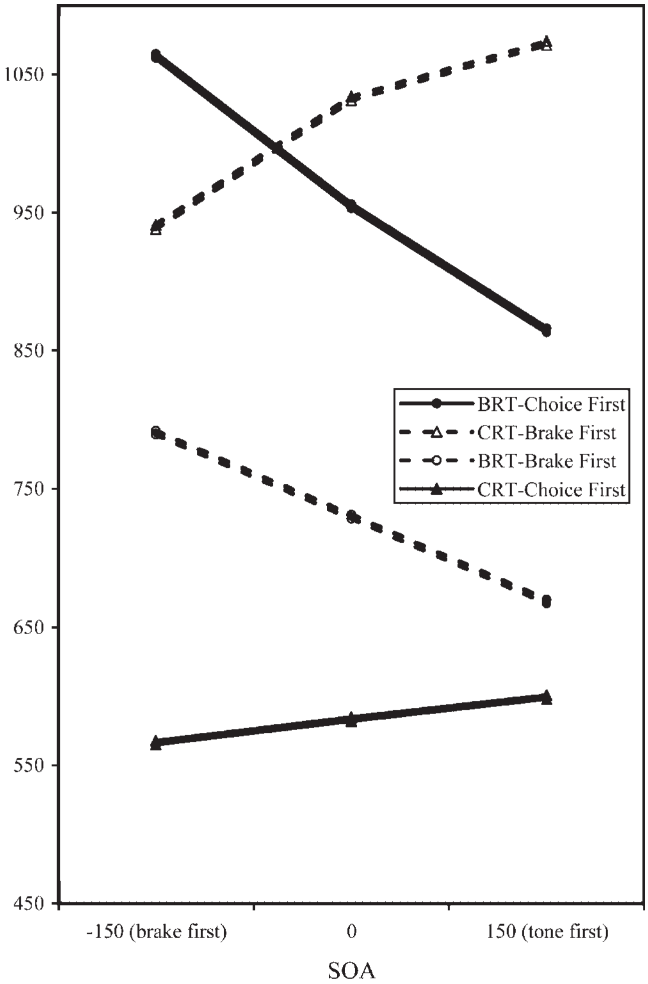

Figure 2. Choice and braking reaction times as a function of SOA, partitioned by First Response, Experiment 1

would be partitioned in this bin. As a result, the average braking RTs should be slower in the $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$ than in the $\mathrm{SOA}_{150\ \mathrm{tone\ first}}$ condition. Therefore, the braking RT curve should be negatively sloped across SOA; the reverse logic accounts for the positive slope of the choice RT curve.

It may be helpful at this point to recall that the likelihood that the First Response was to the braking task was highest at $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$ and lowest at $\mathrm{SOA}_{150\ \mathrm{tone\ first}}$. This finding intuitively fits with the notion of a race to the bottleneck: earlier presentation of a task's stimulus results in a higher likelihood that this task's response will win the race. The dependent measure here (percentage) is not subject to a selection bias like the RT measure mentioned above.

In order to gauge the extent to which responding to one task delays responding to the other task, we computed the IRI on each trial. When the First Response was to the choice task, the IRIs (with standard error) for the $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$, SOA_0 and $\mathrm{SOA}_{150\ \mathrm{tone\ first}}$ were

362 (17.4), 385 (17.4) and 426 (17.4) milliseconds, respectively. The effect of SOA was significant, $F(2, 46) = 3.52, p < 0.04$. When the First Response was to the braking task, the IRIs (with standard error) were −286 (15.8), −293 (15.8) and −250 (15.8) milliseconds for the three SOA levels. This result did not reach significance, $F(2, 42) = 2.09, p < 0.13$. The magnitude (and change in sign) of the IRIs implies that responding to one task imposes a significant delay in responding to the other task. Concretely, when the responding order was choice-then-braking, choice RTs were fast but braking RTs were relatively slow, and with the opposite responding order braking RTs were fast and choice RTs were relatively slow. Thus, the IRI results show that the Second Response was emitted substantially later than the First Response, an outcome entirely consistent with serial processing models.

Because different percentages of trials contributed to the two First Response sortings, we must be cautious in overinterpreting the data. Nonetheless, the differences in RTs for each task are striking by whether it was the First or Second Response. Braking RTs increased by about 30% when it was the Second Response compared to when it was the First Response. The increase in choice RTs was even more dramatic: 70% when it was the Second Response. Thus, the RTs for both the choice and braking tasks were substantially slower when it was the Second Response than when it was the First one (for choice response, around 300–350 milliseconds slowing; for braking responses, around 200–300 milliseconds).

Single-versus dual-task comparisons

Comparing performance between the single- and dual-task conditions is not as straightforward as one might at first expect. As the dual-task analyses make clear, the RTs to each task depended strongly by whether it was made as the First or Second Response. Further, the IRI analyses showed that there was sizeable slowing for each response when it was the Second Response. Therefore, collapsing across Response Order bins would in effect mix different samples into a single 'dual-task' measure. This would ignore the insight gained from the above analyses and likely have little value. However, examining RTs separately by Response Order is not without shortcomings, either. This is because, as mentioned above, the data were partitioned by performance, not an experimental variable. Different percentages of trials constitute each bin and the computed values contain some skew, given the inclusion bias. Nonetheless, we believe this is the better of the two options, as this at least provides some clue about how single-task performance compares to dual-task conditions containing fast and slow reactions (First and Second Response bins, respectively). Hence, we compared single-task performance with dual-task performance, separately for each bin of Response Order, by collapsing the data across redundant signal and SOA (for the dual-task trials).

When choice was the First Response, choice RTs were faster under the dual- than single-task condition (584 and 626 milliseconds, respectively), and this difference was significant, $F(1, 21) = 26.45$, $p < 0.01$. However, when braking was the First Response, choice RTs were slower under the dual-task (1017 milliseconds) than single-task condition, $F(1, 21) = 85.56$, $p < 0.01$. A similar pattern was obtained for the braking RTs. When braking was the First Response, braking RTs were faster under the dual- than single-task condition (735 and 884 milliseconds, respectively), $F(1, 21) = 52.55$, $p < 0.01$, but when choice was the First Response, braking RTs were slower under the dual-task (963 milliseconds) than single-task condition, $F(1, 21) = 8.90$, $p < 0.01$. Thus, for both the choice and braking responses, the RTs in the single-task condition were intermediate between the performance partitioned to the First Response bin and the Second Response bin. This pattern fits nicely with the notion of a 'race to the bottleneck'. Dual-task performance for the Second Response bin was slower than single-task performance, a straightforward prediction of the bottleneck model, given the processing delay suffered by the 'second task'. Faster performance of dual-task trials in the First Response bin compared to the single-task condition is consistent with the idea that inclusion in the First Response bin reflects at least some bias for fast responses.

Relevance to driving and theoretical implications

Given the substantial degree of slowing on the second-performed task and the IRIs (on the order of hundreds of milliseconds), it becomes crucial to promote responding first to the driving-related task over the -unrelated task. Small increases in the probability that the brake response will be the first response (e.g. via redundant signals) could result in large speed-ups of RT: the relatively small speed-up gained by the tactor (40–75 milliseconds in the single-task condition) could conceivably result in substantially faster braking RTs in the dual-task condition (200–300 milliseconds on some trials). In the real-world such speed-ups may have important consequences, as Evans (1991) notes, '(small) reductions in RT can still reduce the probability and severity of [vehicle] crashes in many cases' (p. 128).

On the theoretical level, the IRIs were substantially different than zero, which argues strongly against the possibility that participants were grouping their two responses into a 'single couplet' of responses. In contrast, the fact that the IRIs differ substantially from zero for *both* tasks is quite consistent with a serial model of dual-task performance, where the response to either task may be handled first, thereby resulting in a delay in the other task.

The redundant signal resulted in faster responses in single-task conditions and as well as an increase of about 5% in the likelihood that the braking response would be emitted first on dual-task trials. This not only is consistent with the RSE obtained with laboratory studies using single-task conditions, but it extends the effect to a more practically relevant context involving dual-task performance. However, we cannot preclude the possibility that faster responses could have solely resulted from faster processing to the tactor, rather than the combination of the two signals, because our experimental design did not include a condition where the tactor was presented alone (i.e. in the absence of the brake light).[12] Still, the previous research on the RSE would argue that the speed-up is due to multiple signals.

EXPERIMENT 2

In order to explore the generalisability of presenting a cross-modal, redundant signal to the lead car's brake lights, Experiment 2 examined the effect of presenting the sound of screeching tyres. All remaining aspects of this experiment were the same as Experiment 1.

Method

Participants

Thirty-five students at the University of California, San Diego, participated in two 1-hour sessions. The only restrictions were that participants had at least 2 years of driving

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[12] We thank one of the reviewers for bringing this point to our attention.

experience prior to participation and had not participated in the previous experiment. On average, those participating had been licensed for 63 months.

Apparatus and simulator
The same apparatus was used as in Experiment 1 except for the redundant signal: here, the sound of screeching tyres was presented over the headphones, starting at the same time as the brake light illumination, and lasting 400 milliseconds. Although both this redundant signal and the stimulus for the choice task were presented in the same modality, each was easily discriminable.

Design and procedure
The instructions were the same as in Experiment 1 except for the description of the redundant signal. Otherwise, all other aspects of the design and procedure were the same.

RESULTS AND DISCUSSION

The data were analysed as in Experiment 1.

Choice response made

We again first examined the extent to which participants withheld making a choice response on dual-task trials. We computed the percentage of trials with a choice response for each level of SOA. Thirty-one of the 35 participants (88.6%) had scores over 80% for all SOA levels and were binned as high-responders. One subject had scores above and below 80% (73.3–88.3%) and therefore was not binned with the high-responders. The three remaining participants (8.6%) did not exceed 66% on any level and were binned as low-responders (scores ranged from 8.3% to 65.8%). Because so few participants constituted the mid- and low-responder groups, analyses were conducted only for the high-responder group.

Single-task performance

Braking RTs were reliably faster on single-task trials under the lights + screech condition (784 milliseconds, SE = 9.7) than lights-only (922 milliseconds, SE = 9.7), $F(1, 30) = 100.36$, $p < 0.01$. The choice RTs and per cent correct scores were 556 milliseconds (SE = 19.2) and 94.5 (SE = 0.7).

Dual-task performance

For dual-task trials, the percentage of trials where braking was the First Response was computed for each factorial combination of SOA and redundant signal. The per cent scores (with standard error) for the $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$, SOA_0 and $\mathrm{SOA}_{150\ \mathrm{tone\ first}}$ were: with redundant signal, 57.1 (1.2), 36.9 (1.2) and 14.3 (1.2), respectively; without redundant signal, 40.5 (1.2), 24.1 (1.2), 8.3 (1.2), respectively. The same pattern was obtained as in Experiment 1: the highest percentage of trials with braking as First Response was at the $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$, and the percentage decreased monotonically across SOA, $F(2, 60) = 122.06$, $p < 0.01$. Additionally, the advantage of screeching tyres was reliable across all levels of SOA, $F(1, 30) = 54.43$, $p < 0.01$, showing a higher likelihood of braking as

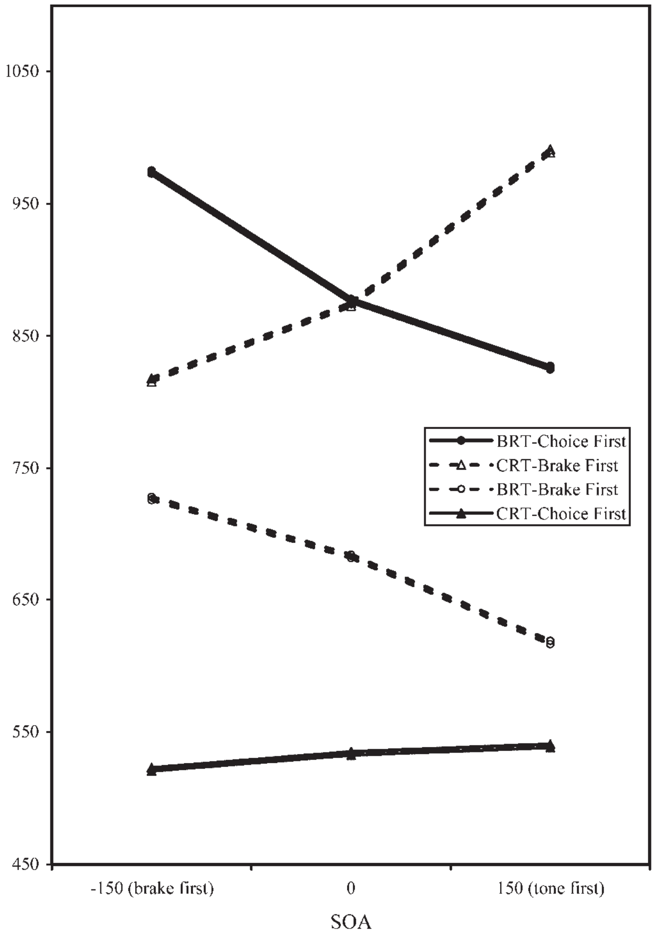

Figure 3. Choice and braking reaction times as a function of SOA, partitioned by First Response, Experiment 2

First Response with the presence of the redundant signal compared to its absence. Additionally, the interaction was significant, $F(2,60) = 9.97, p < 0.01$. Thus, both factors of SOA and redundant signal promoted braking being the First Response.

We again analysed the RT data for both tasks, separately by First Response, and present the data in Figure 3. We tested the effects of SOA and responding order, and similar results were obtained as in Experiment 1. Again, each dependent variable was faster when it was the First Response than the Second Response. For choice RTs, both the effects of SOA and Response Order were significant, $F(2, 52) = 35.79$, $p < 0.01$ and $F(1, 26) = 217.09$, $p < 0.01$, respectively; so too was the interaction, $F(2, 52) = 25.02$, $p < 0.01$. For braking RTs, both the effects of SOA and response order were significant, $F(2, 52) = 123.32$, $p < 0.01$ and $F(1, 26) = 132.04$, $p < 0.01$; the interaction was also significant, $F(2, 52) = 3.59$, $p < 0.04$. Thus, once again each dependent measure was faster when it served as the First Response than as the Second Response, consistent with the 'race to the bottleneck' hypothesis.

We computed the IRI on dual-task trials as in the previous experiment. When the First Response was to the choice task, the IRIs for the $\mathrm{SOA}_{-150\ \mathrm{brake\ first}}$, SOA_0 and $\mathrm{SOA}_{150\ \mathrm{tone}}$

$_{\text{first}}$ were 321 (SE = 9.3), 363 (SE = 9.3) and 452 (SE = 9.3) milliseconds, respectively, and the effect of SOA was significant, $F(2, 60) = 51.86$, $p < 0.01$. When the First Response was to the braking task, the IRIs for the three SOA levels were -241 (SE = 14.8), −190 (SE = 14.8) and −222 (SE = 14.8) milliseconds, respectively, and this was just shy of significance, $F(2, 52) = 2.93$, $p < 0.06$. Again, the IRIs were plainly different than zero, providing additional evidence against the possibility that participants were grouping their two responses into a 'single couplet' of responses. As in Experiment 1, the fact that the IRIs differ from zero for *both* tasks is consistent with a serial model of dual-task performance, where the response to either task may be handled first, thereby resulting in a delay in the other task.

Single- versus dual-task comparisons

We compared performance of each task in the single- and dual-task conditions as in Experiment 1 and obtained the same pattern of results. When choice was the First Response, choice RTs were faster under the dual- than single-task condition (533 and 560 milliseconds, respectively), $F(1, 26) = 6.84$, $p < 0.02$. However, when braking was the First Response, choice RTs were slower under the dual-task (895 milliseconds) than single-task condition, $F(1, 26) = 230.77$, $p < 0.01$. A similar pattern was obtained for the braking RTs. When braking was the First Response, braking RTs were faster under the dual- than single-task condition (677 and 836 milliseconds, respectively), $F(1, 26) = 90.37$, $p < 0.01$, but when choice was the First Response, braking RTs were slower under the dual-task (894 milliseconds) than single-task condition, $F(1, 26) = 27.37$, $p < 0.01$. Thus once again for both the choice and braking responses, the RTs in the single-task condition were intermediary between the performance partitioned to the First Response bin and the Second Response bin.

Overall, the pattern of results in this experiment was the same as in Experiment 1. There was a benefit of the (auditory) redundant signal. Compared to the lights-only braking condition, the lights + screech condition resulted in faster braking RTs on single-task trials as well as an increase of about 6–16% in the likelihood that the braking response would be emitted first on dual-task trials. Both braking and choice RTs were markedly faster when each served as the First Response than Second Response (within task comparison), and the IRIs for each task were sizable (between task one). Thus, the findings in this experiment closely match those of the previous experiment and again fit with the notion of a 'race to the bottleneck'. We therefore refrain from repeating the arguments presented in the previous experiment's discussion.

GENERAL DISCUSSION

We obtained strikingly similar results across two experiments[13] designed to test a number of issues related to multitasking in the driving domain. The first question we posed was whether people can interrupt the performance of one task in favour of a driving task that is

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[13] In actuality, we conducted an additional experiment, similar to Experiment 2 except that the redundant signal was presented whenever the lead car's brake lights were activated (i.e. 100% co-occurrence). We wanted to determine whether participants' performance would improve (e.g. whether there would be a higher percentage of braking First Response trials and/or increased likelihood of not responding to the choice task) if the redundant signal was completely reliable. The results mimicked those of the other experiments, with the exception that a larger percentage of participants were binned as mid-responders (27.1%, or $n = 16$). However, like Experiments 1 and 2, the majority of participants were high-responders (64.4%, or $n = 38$), with only a minority binned as low-responders (8.5%, or $n = 5$).

assigned high priority. One might expect this to be possible not only because the experimental instructions demanded such priority, but also because the driving action involved avoiding danger, and corresponded closely to a task that they would have extensively practiced in their natural environments, where it was also presumably viewed as having high priority. Despite all these factors that would seem to encourage subjects to abort the concurrent task in favour of the braking task, the results showed that most of people most of the time did not succeed in aborting their response to the low-priority task. This failure to abort the low-priority task resulted in significant time delays in braking responses. Only a small minority of participants successfully withheld a response to the low-priority task most of the time and avoided delays in responding to the higher priority task.

At a more detailed level, perhaps the most interesting findings to emerge from our studies relate to the 'First Response'. We partitioned trials where responses were made to both tasks according to whether the response to the braking task preceded or followed the response to the choice task. The RTs for either task were hundreds of milliseconds faster when they were the First Response than the Second Response. From a practical perspective on multitasking, this suggests the importance of promoting first responding to the high-priority task. The two factors manipulated here—SOA and redundant signal—both had significant effects resulting in increased likelihood that the braking response would precede the choice response. Across the experiments, the obtained probabilities were remarkably consistent: roughly 54, 38 and 19 per cent across the $SOA_{-150\text{ brake first}}$, SOA_0 and $SOA_{150\text{ tone first}}$ levels, respectively, with the redundant signal, compared to roughly 44, 30 and 14 per cent, respectively, without the redundant signal.

From a theoretical perspective, the results are generally consistent with the CB model (Pashler, 1994, 1998; Welford, 1952). As discussed in the Introduction Section, this theory posits that serial processing between tasks is obligatory for certain mental operations (e.g. response selection and planning) but not others (e.g. perception and response execution). Thus, when these bottleneck-prone processes are underway in one task, corresponding operations in any other task must be delayed. While the model has received much support from laboratory studies, these studies normally involved a person instructed to complete both of two tasks. By contrast, in real-world multitasking environments (e.g. driving) it would often be sensible to give one of the tasks vastly higher priority than others. This highlights the importance of the question explored here, namely how readily a task can be aborted in favour of a higher priority task. Past research suggested that this is possible in principle at least some of the time (Logan & Burkell, 1986), and the present studies confirm that for some people some of the time, aborting of the low-priority task was achievable, presumably resulting in reduced interference on the high-priority task. However, looking across the studies reported here, it is remarkable how often the response to a lower-priority task was emitted before the high priority one, with the consequent delay of the high-priority task.

At this point, it seems that no simple statement can be made about which of two tasks gains access to (and continues to occupy) the central mechanism on any trial. Aside from intentional goal setting, one plausible account is that the task that gains access to the central mechanism is the one whose early processing is completed first. We refer to this as a 'race to the bottleneck'. A race model is potentially compatible with the RSE observed here, where responses are faster and interruption more frequent when redundant signals are presented for the braking task, rather than just one. A candidate locus of this effect is a speed-up in pre-central processing, possibly involving some multimodal perceptual stage

(Cavina-Pratesi et al., 2001; see also Miller, 1982). This in turn could increase the likelihood that the high-priority task can engage the central mechanism before the other task. The race idea is obviously also consistent with the effects of SOA observed here.

The present study is a follow-up to a previous one from our laboratory (Levy et al., 2006), which used the same simulator and apparatus (but without the redundant signals) and employed the same braking and choice tasks. The major difference was that in the earlier study, participants were instructed always to respond to the choice task, the signal for which was never preceded by the signal to brake. As mentioned in the Introduction Section, in that situation the braking RTs reliably exhibited obvious dual-task slowing taking the form of a PRP effect (greater slowing at shorter SOAs). In an attempt to determine if requiring a choice response results in slower braking RTs than allowing drivers not to respond to the choice task (as in the present experiment), we compared the braking RTs from the previous experiment (limited to trials where the choice task was with an auditory stimulus and manual response at the SOA_0 condition) with braking RTs from Experiment 1. Braking RTs were slower in the previous study than in the present one both when the braking response was the First and Second Response, $F(1, 54) = 44.26$, $p < 0.01$ and $F(1, 54) = 8.30$, $p < 0.01$, respectively. We must be cautious in interpreting these between-experiment comparisons, but they suggest that braking responses suffer greater interference when a response to a different task is required compared to the driver having the option to withhold that response.

Implications for man-machine interface

The CB model and the results of the present studies have potential design implications concerning in-vehicle warning systems. First, braking RTs were faster with signals that are redundant to the traditional braking signal (i.e. the brake lights of the lead vehicle). Rather than causing distraction or interference, the redundant signals led to faster braking RTs under single-task conditions and a higher likelihood on dual-task trials that the braking response would precede the choice one, which in turn resulted in substantially faster braking RTs. Second, the SOA manipulation showed that very small intervals (150 milliseconds) had a substantial effect on the likelihood of braking being the First Response. An integrated in-vehicle system that facilitates both collision avoidance and presentation of other information to the driver (e.g. telematics) could delay the presentation of lower-priority signals when the system 'anticipates' the imminent presentation of warning signals. Appropriate delays (even if relatively brief, as employed in these experiments) would increase the likelihood of the high priority signal 'winning the race', and thereby lead to faster braking RTs. Alternatively, the lower priority signals could be withheld altogether under certain conditions, thereby obviating the need for the race altogether and guaranteeing no dual-task interference (we term this related strategy as 'cancelling' the race).

Limitations

The above studies were conducted in the laboratory using a PC-based driving simulator. The advantage of this, of course, is that it easily allowed for millisecond timing and recording of events, crucial for our manipulations and analyses, with no potential for serious personal injury or property damage. One obvious shortcoming of this methodology is that the question remains open whether drivers in a vehicle on the road—where real damage and injury are possible—might respond differently, and interrupt processing the

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lower priority task in favour of braking. However, despite the possibility of real-world consequences, it has been estimated that the majority (approximately 68%) of rear-end collisions are due to driver inattention or distraction (Knipling, Wang, & Yin, 1993).

Two particulars of the design should be mentioned that may have a bearing on the results. First, the choice task involved briefly presented tones and required a punctate response, and thus the time course of the entire task (from stimulus to response) was relatively brief (under 700 milliseconds). It is not clear how more prolonged engagement in an on-going task (e.g. conducting a conversation) might affect inter-task interference and the possibility for interruption. Recent work from our laboratory (Pashler, Levy, and Johnston, submitted) suggests that braking responses would be slower if the other task were more engaging (that is, performed repeatedly rather than just one time). We hypothesised in that study that the slowing on the second task occurred because the participants' 'task set' (i.e. their readiness to perform that task) weakened as they became more engaged in the other task.

The second issue, related to the first, is the particular proportion of braking opportunities employed in these experiments: a braking response was required in more than half of the trials (36 dual-task and16 brake-only trials per block of 88 trials, which is about 60%). In selecting this proportion of braking/no-braking trials, we were not attempting to simulate any particular traffic condition, even though it seems likely that the task set for braking is affected by its frequency of performance. That said, one could argue that the implications for the real-world are considerable, because the circumstances of this study provided a greater opportunity for repeated engagement in the braking task than would typical highway driving, which usually entails much less frequent braking.

In summary, previous research has shown that central processing operations involved in driving and other tasks are usually subject to a CB, entailing sequential central processing, but this research has suggested that the possibility exists that people can abort one task in progress in favour of a higher priority process, potentially minimising the consequences of central interference. However, the current results show that while low-priority tasks may be aborted, they frequently are not, resulting in substantial delays in responding to the high-priority task.

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