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Cell Phone-Induced Failures of Visual Attention During Simulated Driving

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This research examined the effects of hands-free cell phone conversations on simulated driving. The authors found that these conversations impaired driver's reactions to vehicles braking in front of them. The authors assessed whether this impairment could be attributed to a withdrawal of attention from the visual scene, yielding a form of inattention blindness. Cell phone conversations impaired explicit recognition memory for roadside billboards. Eye-tracking data indicated that this was due to reduced attention to foveal information. This interpretation was bolstered by data showing that cell phone conversations impaired implicit perceptual memory for items presented at fixation. The data suggest that the impairment of driving performance produced by cell phone conversations is mediated, at least in part, by reduced attention to visual inputs.

Cellular phones are now ubiquitous, with more than 137 million subscribers in the United States as of December 1, 2002 (Cellular Telecommunications Industry Association, 2002). There has also been a corresponding increase in the number of individuals talking on the phone while driving. Indeed, recent estimates suggest that 85% of cell phone owners use their phone while driving (Goodman et al., 1999) and that 60% of cell phone owner's usage occurs while driving (Hahn, Tetlock, & Burnett, 2000). Because of safety concerns, several legislative efforts have been made to restrict cell phone use on the road. In most cases, the legislation regarding cell phones and driving focuses on peripheral factors such as dialing or holding the phone while conversing. For example, in the summer of 2001, the state of New York passed a law banning the use of handheld phones while driving yet permitted drivers to use hands-free cell phones (Chapter 69 of the Laws of 2001, section 1225c State of New York).

In fact, prior research has established that the manual manipulation of equipment (e.g., dialing the phone and answering the phone) does have a negative impact on driving (e.g., Briem & Hedman, 1995; Brookhuis, De Vries, & De Waard, 1991). However, the distracting effects of the phone conversation on driving are also considerable, and the duration of a typical phone conversation can be up to two orders of magnitude greater than the time required to dial or answer the phone. On the one hand, Briem and Hedman (1995) reported that simple conversations did not adversely affect the ability to maintain road position. On the other hand, several studies have found that working memory tasks (Alm & Nilsson, 1995; Briem & Hedman, 1995), mental arithmetic tasks (Harbluk, Noy, & Eizenmann, 2002; McKnight & McKnight, 1993), and reasoning tasks (I. D. Brown, Tickner, & Simmonds, 1969) disrupt driving performance.

Our earlier research found that participants engaged in cell phone conversations were more likely to miss traffic signals and reacted to the signals that they did detect more slowly than when they were not engaged in cell phone conversations (Strayer & Johnston, 2001). Moreover, equivalent deficits in driving performance were obtained for both users of handheld and hands-free cell phones. By contrast, listening to radio broadcasts or books on tape did not impair driving performance. In a similar vein, McCarley et al. (2001) found impairments in the ability of participants to detect changes in real-world traffic scenes when they were conversing on a hands-free device; however, no such performance decrements were observed when participants listened to prerecorded conversations from other participants. These findings are important because they demonstrate that listening to verbal material, by itself, is not sufficient to produce the dual-task interference associated with using a cell phone while driving. In our earlier work, we suggested "that cellular-phone use disrupts [driving] performance by diverting attention to an engaging cognitive context other than the one immediately associated with driving" (Strayer & Johnston, 2001, p. 466).

In fact, evidence from a wide variety of sources has established a link between attention and driving. For example, a recent study of 723 crashes found that 37.8% of the accidents were due to driver inattention or perceptual errors (Hendricks, Fell, & Freedman, 1999). Earlier, Treat et al. (1979) evaluated 2,258 traffic accidents and concluded that improper lookout and inattention were the two leading causes of the traffic accidents. Attention errors have been reported to be the most common factor in left-turn accidents, and this trend is up to six times more pronounced in older drivers (Keskinen, Ota, & Katila, 1998; Larsen & Kines, 2002; U.S. Department of Transportation National Highway Traffic Safety Administration, 2000). Drivers are also more likely to collide with stationary vehicles when attention is disrupted by a secondary task (Langham, Hole, Edwards, & O'Neil, 2002). Additionally, laboratory-based selective-attention tasks (Arthur & Doverspike, 1992) and attention-switching tasks (Elander, West, & French, 1993; Moss & Triggs, 1997) have been found to predict traffic accidents. There is also evidence that drivers develop attentional

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strategies that focus on areas of expected hazards, at the expense of processing less frequent hazards (Summala, Pasanen, Raesaenen, & Sievaenen, 1996). Together, these observations establish a clear-cut association between attention and driving performance.

We had two objectives in the current research. The first objective was to replicate and extend our earlier findings using a high-fidelity driving simulator. One might argue that the reason that cell phone conversations disrupted performance in our earlier studies was that participants were not as familiar with the pursuit-tracking and change-detection tasks as they were with driving. That is, a more well-practiced skill such as driving may be less sensitive to the distraction produced by cell phone conversations than are less familiar laboratory-based tasks. We assessed this possibility in Experiment 1 and found cell phone conversations to impair driving performance in a high-fidelity driving simulator.

The second objective of our research was to assess Strayer and Johnston's (2001) hypothesis that cell phone conversations impair driving performance by withdrawing attention from the visual scene, yielding a form of inattention blindness. Experiments 2–4 examined the effects of cell phone conversations on attention to objects in the visual field during simulated driving. Reduced attention to visual inputs would support an inattention-blindness interpretation.

Experiment 1

Our first study was designed to replicate and extend the findings of Strayer and Johnston (2001) using a high-fidelity driving simulator. We used a car-following paradigm (see also Alm & Nilsson, 1995; Lee, Vaven, Haake, & Brown, 2001) in which participants drove on a multilane freeway in single-task (i.e., driving only) and dual-task (i.e., driving and conversing on a cell phone) conditions. Traffic density (low vs. high) was also manipulated. Participants followed a pace car that would brake at random intervals. We measured a number of real-time performance variables to determine how participants reacted to the car braking in front of them.

Method

Participants. Forty undergraduates (18 men and 22 women) from the University of Utah participated in the experiment. Participants ranged in age from 18 to 32, with an average age of 23.6. All had normal or corrected-to-normal visual acuity, normal color vision (Ishihara, 1993), and a valid Utah driver's license. Of the 23 participants who reported that they owned a cellular phone, 83% reported that they used their phone while driving.

Stimuli and apparatus. A PatrolSim high-fidelity driving simulator, manufactured by GE Capital I-Sim (Salt Lake City, UT) was used in the study. The simulator comprises five networked microprocessors and three high-resolution displays, providing a 180° field of view. The dashboard instrumentation, steering wheel, gas pedal, and brake pedal are from a Ford Crown Victoria sedan, with an automatic transmission. The simulator incorporates proprietary vehicle dynamics, traffic scenario, and road surface software to provide realistic scenes and traffic conditions. Measures of real-time driving performance, including driving speed, distance from other vehicles, brake, gas, and steering wheel inputs, were sampled at 30 Hz and stored for later analysis.

A freeway road database was used to create the scenarios for the experiment. The freeway road database simulated a 40-mile (64-km) multilane beltway with on- and off-ramps, overpasses, and two- and three-lane traffic in each direction (separated by a grass median). All scenarios used daytime dry-pavement driving conditions with good visibility. In the low-density driving condition, a pace car and the participant's car were the only vehicles on the roadway. The pace car was programmed to stay in the right-hand lane throughout the scenario. In the high-density driving condition, 32 "distractor" vehicles were added to the highway scenario. These distractor vehicles were programmed to drive between 5% and 10% faster than the pace car in the left lane, providing the impression of a steady flow of traffic in the left-hand lane. In each scenario, the pace car was programmed to brake at 32 randomly selected intervals and would continue to decelerate until the participant depressed the brake pedal, at which point the pace car would begin to accelerate to normal freeway speeds. The brake lights of the pace car were illuminated throughout the deceleration interval. Thus, each scenario provided 32 opportunities to measure the participant's response to a car braking in front of them.

Procedure. When participants arrived for the experiment, they completed a questionnaire that assessed their interest in potential topics of cell phone conversation. Participants were then familiarized with the driving simulator using a standardized 20-min adaptation sequence. Participants then drove four 10-mile (16-km) sections on a multilane highway. Half the scenarios were used in the single-task driving condition and half were used in the dual-task (i.e., driving and cell phone conversation) condition. The order of conditions and scenarios was counterbalanced across participants using a Latin square design, with the constraint that both single- and dual-task conditions were performed in the first half of the experiment and both single- and dual-task conditions were performed in the last half of the experiment. For data analysis purposes, the data were aggregated across scenarios for both the single- and dual-task conditions.

The participant's task was to follow a pace car that was driving in the right-hand lane of the highway. When the participant stepped on the brake pedal in response to the braking pace car, the pace car released its brake and accelerated to normal highway speed. If the participant failed to depress the brake, he or she would eventually collide with the pace car. That is, like real highway stop-and-go traffic, the participant was required to react in a timely and appropriate manner to vehicles slowing in front of them. Traffic density was also manipulated by changing the number of vehicles on the highway. The manipulation of traffic density primarily affected perceptual load; neither the participant nor the pace car directly interacted with these distractor vehicles, as they were traveling in different lanes.

The dual-task condition involved conversing on a cell phone with a confederate. The participant and the confederate discussed topics that were identified in the preexperiment questionnaire as being of interest to the participant. To avoid any possible interference from manual components of cell phone use, participants used a hands-free cell phone that was positioned and adjusted before driving began. Additionally, the call was initiated before participants began the dual-task scenarios. Thus, any dual-task interference observed must be due to the cell phone conversation itself, because there was no manual manipulation of the cell phone during the dual-task portions of the study.

Dependent measures. Four parameters associated with the participant's reaction to the braking pace car were examined. *Brake-onset time* was defined as the interval between the onset of the illumination of the pace car's brake lights and the onset of the participant's brake pedal depression. *Brake-offset time* was defined as the interval between brake onset and the time that participants released their foot from the brake pedal. *Time to reach minimum speed* was defined as the time at which the participant's vehicle stopped decelerating and began to return to normal highway speed. *Following distance* was the distance in meters between the pace car and the participant's car. Finally, whether participants were involved in any collisions during the study was also monitored.

Design and statistical analysis. The design was a 2 (traffic density: low vs. high) × 2 (task: single vs. dual) factorial. Traffic density was a between-subjects factor, and single- versus dual-task condition was a within-subjects factor. It is very likely that the dependent measures described above are not independent. For example, the time to reach minimum speed is likely to be influenced by both brake-onset and brake-offset time. Likewise, both brake-onset and brake-offset times are likely to be influenced by following distance. A multivariate analysis of variance (MANOVA) was used to provide an overall measure of driver performance as a function of experimental conditions. One important advantage of the MANOVA is that it provides an assessment of the unique variance and the overall effect size associated with the experimentally manipulated variables. Univariate analyses were also performed on each of the dependent measures using a 2 (traffic density: low vs. high) × 2 (task: single vs. dual) split-plot analysis of variance (ANOVA). A significance level of $p < .05$ was adopted for all inferential tests reported in this article. Cohen's *d*, which provides a measure of the standardized difference between group means, was used to estimate effect size for all analyses reported in this article. Cohen (1988) provided a heuristic for interpreting measures of *d*, in which a small effect size would have a value of .20, a medium effect size would have a value of .50, and a large effect size would have a value of .80.

Results and Discussion

Table 1 presents the accident rates and the four dependent measures described above. There were no accidents in the low-density condition. However, participants were more likely to be involved in traffic accidents while conversing on a cell phone in the high-density condition. In all cases, the collision was the result of the participant rear-ending the braking pace car (cf. T. L. Brown, 2001). To better understand this increased incidence of traffic accidents, we examined the driver's speed, brake response, and the distance from the pace car.

Inspection of Table 1 reveals that participants initiated their braking response approximately 1 s after the pace car's brake lights were illuminated and that the participant kept their foot on the brake for about ½ s following brake onset. The driving speed measures indicated that the participant's vehicle continued to decelerate for several seconds after the pace car's brake lights were illuminated; thereafter, the participant's vehicle gradually accelerated to normal freeway speeds. Participants also increased the separation between themselves and the pace car when they were conversing on the cell phone.

Table 1
Driving Performance From Experiment 1

Variable	Low-traffic density	High-traffic density
Traffic accidents		
Single task	0	0
Dual task	0	3
Brake onset (msec)		
Single task	928 (83)	933 (69)
Dual task	957 (64)	1,112 (78)
Brake offset (msec)		
Single task	621 (65)	580 (53)
Dual task	688 (63)	653 (56)
Time to min speed (msec)		
Single task	1,833 (57)	1,920 (25)
Dual task	2,130 (25)	2,430 (28)
Following distance (m)		
Single task	23.6 (1.9)	25.8 (1.2)
Dual task	26.0 (1.8)	29.3 (1.4)

Note. Standard errors appear in parentheses. min = minimum.

The inferential statistics for Experiment 1 are presented in Table 2. The MANOVA revealed a significant main effect of single- versus dual-task condition, indicating that when participants were conversing on the cell phone, their reactions were sluggish when compared with their single-task baseline. Participants attempted to compensate for this sluggish behavior by increasing the separation between themselves and the pace car. In addition, the difference between single- and dual-task conditions was exacerbated by traffic density.

Subsidiary univariate analysis revealed that brake-onset times were longer in dual-task than in single-task conditions. Planned comparisons revealed that the difference between single- and dual-task conditions was not significant in the low-density condition but differed significantly in the high-density condition. Brake-offset times were also longer in dual- than in single-task conditions. Neither the main effect of traffic density nor the interaction of traffic density with single- versus dual-task condition was significant. These data indicated that participants conversing on a cell phone were slower to initiate their braking response and continued to press the brake pedal longer when they were driving in dual-task conditions.

Participants also took longer to reach the nadir of their speed in dual-task conditions than in single-task conditions. Again, neither the main effect of traffic density nor the interaction of traffic density with single- versus dual-task conditions was significant. However, planned comparisons revealed that the difference between single- and dual-task conditions was not significant in the low-density condition but was significant in the high-density condition.

Inspection of Table 1 also reveals that participants increased the separation between themselves and the pace car from single- to dual-task conditions. Neither the main effect of traffic density nor the interaction of traffic density with single/dual-task conditions was significant. Indeed, planned comparisons revealed that the increase from single- to dual-task conditions was significant for both the low-density and high-density conditions.

Taken together, the data from Experiment 1 demonstrated that conversing on a hands-free cell phone impaired driving performance and that this impairment became more pronounced as traffic density increased. Consistent with this finding, participants were more likely to be involved in traffic accidents when they were using the cell phone in the high-density driving conditions. The interaction of single- versus dual-task conditions and traffic density is interesting because this manipulation was accomplished solely by changing the number of distractor vehicles in the lane adjacent to the participant's vehicle. Neither the participant nor the pace car directly interacted with these distractor vehicles. Lee et al. (2001) also found that dual-task interference increased as the perceptual complexity of the driving environment increased. These authors suggested that "the more [perceptually] complex environment exposes drivers to more abrupt onsets in the visual field" . . . and that ". . . these onsets may attract visual attention and distract the driver from the roadway, inducing a degree of change or inattention-blindness" (p. 638). Such an interpretation is consistent with the inattention-blindness hypothesis proposed by Strayer and Johnston (2001).

It is noteworthy that these performance decrements were obtained even when there was no possible contribution from the manual manipulation of the cell phone. Thus, these data replicate

Table 2
Multivariate and Univariate Inferential Statistics for Experiment 1

Variable	Λ	*F*	*d*
	MANOVA		
Task	0.65	4.8^{a}	0.74**
Traffic density	0.85	1.5^{a}	0.42
Task × Traffic Density	0.77	2.6^{a}	0.54*
	Univariate statistics		
	MSE	*F*	*d*
Brake-onset			
Task	29,572	7.3^{b}	0.88**
Traffic density	188,975	0.7^{b}	0.27
Task × Traffic Density	29,572	3.8^{b}	0.64
Task at low density	$t(19) = 0.8$		0.1
Task at high density	$t(19) = 2.6$		0.6**
Brake-offset			
Task	11,749	7.2^{b}	0.87**
Traffic density	130,421	0.3^{b}	0.17
Task × Traffic Density	11,749	0.0^{b}	0.08
Task at low density	$t(19) = 2.9$		0.23**
Task at high density	$t(19) = 1.6$		0.43
Time to reach min. speed			
Task	686	8.1^{b}	0.92**
Traffic density	1,997	0.9^{b}	0.30
Task × Traffic Density	686	0.0^{b}	0.02
Task at low density	$t(19) = 1.5$		0.4
Task at high density	$t(19) = 3.6$		1.1**
Following distance			
Task	10	17.4^{b}	1.4**
Traffic density	96	1.6^{b}	0.41
Task × Traffic Density	10	0.6^{b}	0.25
Task at low density	$t(19) = 2.4$		0.29*
Task at high density	$t(19) = 3.5$		0.58**

Note. MANOVA = multivariate analysis of variance; min. = minimum.
^{a} *dfs* = 4, 35. ^{b} *dfs* = 1, 38.
* $p < .05$. ** $p < .01$.

and extend the findings of Strayer and Johnston (2001) and are consistent with an attention-based interpretation in which the disruptive effects of cell phone conversations on driving are due primarily to the diversion of attention from driving to the phone conversation itself. These findings are also consistent with Rumar's (1990) observation that a basic road user error results from a failure to see and react to another road user in time.

Experiment 2

Our earlier research found that participants driving and conversing on a cell phone missed more traffic signals than when they were driving without the distraction caused by cell phone use (Strayer & Johnston, 2001). Similarly, McCarley et al. (2001) also found that cell phone conversations interfered with change detection in real-world traffic scenes, and the results of Experiment 1 indicated that the driver's reaction to vehicles braking in front of them are slowed when they were engaged in cell phone conversations. One possible interpretation of these findings is that participants using a cell phone detected the imperative signals but that their responses to them were suppressed. However, as noted above, another—and potentially more dangerous—possibility is that the cell phone conversation actually inhibited attention to the external environment. Experiment 2 was designed to examine how cell phone conversations affect the driver's attention to objects that are encountered while driving. We contrasted performance of participants who were driving but not conversing (i.e., single-task conditions) with that of participants who were driving and conversing on a hands-free cell phone (i.e., dual-task conditions).

We used an incidental recognition memory paradigm to assess what information in the driving scene participants attended while driving. The procedure required participants to perform a simulated driving task without the foreknowledge that their memory for objects in the driving scene would be subsequently tested. Later, the participant was given a surprise recognition memory task in which they were shown objects that were presented while they were driving and were asked to discriminate these objects from foils that were not in the driving scene. The incidental recognition memory paradigm assesses participants' explicit memory for these objects (i.e., participants must be able to verbally report that they recognize the object as something they saw while driving). The advantage of this procedure is that it has been well established that attention is necessary for long-lasting explicit memories (e.g., Mack & Rock, 1998; see also Johansson & Rumar, 1966, for a related procedure for assessing how drivers attend to road signs). Therefore, differences in incidental recognition memory between single- and dual-task conditions provides an estimate of the degree to which attention to visual information in the driving environment is distracted by cell phone conversations.

As in Experiment 1, we used a high-fidelity driving simulator that provided an immersive driving context for the participant. In the present study, we used a city-driving scenario in which we positioned a number of digital images of real-world billboards in the driving scene so that they were in clear view as the participant drove past them. Traffic density was not manipulated because of limitations imposed by the driving simulator. After participants completed the driving portion of the experiment, they were given a surprise recognition memory test to determine incidental memory for billboards. If the cell phone conversation inhibits attention to the external environment, then recognition memory for the billboards should be impaired in dual-task conditions.

Method

Participants. Twenty undergraduates (11 men, 9 women) from the University of Utah participated in the experiment. Participants ranged in age from 18 to 24, with an average age of 20.1. All had normal or corrected-to-normal visual acuity, normal color vision (Ishihara, 1993), and a valid Utah driver's license. Each participant served in both single- and dual-task conditions. Of the 15 participants who reported that they owned a cellular phone, 73% reported that they used their phone while driving.

Stimuli and apparatus. The high-fidelity driving simulator was the same as in Experiment 1. A suburban-road database was used to create the scenarios for the experiment. The database simulated a small suburban city with residential, business, and downtown sections extending over an 80-square block area. Within the suburban-road database, six sections of roadway, each 1.2 miles (1.9 km) in length, were selected to create the scenarios used in the experiment. In each of the six scenarios, navigational arrows placed at intersections directed participants to turn right or left. Half the scenarios were used in the single-task condition and half were used in the dual-task condition. Single- and dual-task conditions were blocked, and both task order (single vs. dual task) and driving scenario were counterbalanced across participants.

A central manipulation in the study was the placement of five billboards in each of the scenarios. The billboards were positioned so that they were clearly in view as participants drove past them. A total of 45 digital images of real-world billboards were created using a digital camera. One third of these billboards were presented in the single-task condition, one third were presented in the dual-task condition, and one third were used as control stimuli in an incidental recognition memory task and were not presented in the driving scenarios. The control billboards were included to provide an estimate of the guessing rates in the recognition memory task. A random assignment of billboards to conditions and locations within the scenarios was created for each participant.

Procedure. When participants arrived for the experiment, they completed a questionnaire that assessed their interest in potential topics of cell phone conversation. Participants were then familiarized with the driving simulator using a standardized 20-min adaptation sequence. The experiment involved driving six 1.2-mile (1.9-km) sections of a suburban area of a city. Half the driving scenarios were used in the single-task driving condition and half were used in the dual-task condition. For data analysis purposes, the data were aggregated across scenarios in both the single- and dual-task conditions.

The participant's task was to drive through each scenario, following all the rules of the road. Participants were given directions to turn left or right at intersections by using left or right arrow signs that were placed in clear view of the roadway. Within each scenario, participants made an average of two left-hand and two right-hand turns. In other respects, the driving procedure was identical to Experiment 1. Immediately following the driving portion of the study, participants performed an incidental-recognition-memory task in which they judged whether each of 45 billboards had been presented in the driving scenario (15 of the billboards had been presented in the single-task condition, 15 in the dual-task condition, and 15 were control billboards that had not been presented in the driving portion of the study). Each billboard was presented separately on a computer display and remained in view until the participants made their old/new judgment. There was no relationship between the order of presentation of the billboards in the driving task and the order of presentation in the recognition memory task. Participants were not informed about the recognition memory test until after they had completed the driving portions of the experiment.

Results and Discussion

Table 3 presents the recognition memory data for Experiment 2. The (incorrect) classification of control billboards as "old" was infrequent, indicating a low base rate of guessing. Billboards presented in single- and dual-task conditions were more likely to be classified as "old," with billboards from single-task conditions correctly recognized more often than billboards from dual-task conditions. Planned comparisons revealed that recognition memory was greater in single-task conditions than in dual-task conditions, $t(19) = 4.44$, $p < .01$, $d = 1.1$. Recognition memory for billboards presented in dual-task conditions was also significantly above the guessing control, $t(19) = 4.27$, $p < .01$, $d = 1.4$, indicating that performance in dual-task conditions cannot be attributed solely to guessing. Thus, these data demonstrated that conversing on a cell phone impairs the recognition memory for objects presented in the driving scene.

Table 3
Recognition Memory Performance for Experiment 2

Variable	Single task	Dual task	Control
No. of billboards classified as "old"	6.8 (0.7)	3.6 (0.6)	0.9 (0.3)

Note. Standard errors appear in parentheses. No. = number.

These indications of failures of visual attention extend our earlier observation of higher rates of missing traffic signals while conversing on a cell phone (e.g., Strayer & Johnston, 2001). The data are consistent with the hypothesis that the cell phone conversation disrupts performance by diverting attention from the external environment associated with the driving task to an engaging internal context associated with the cell phone conversation. However, an alternative interpretation of these data is that the impaired recognition memory performance may be due to a disruption of the visual scanning of the driving environment while conversing on the cell phone and not to differences in the perception of objects presented at fixation. This possibility is addressed in Experiment 3.

Experiment 3

Our third study was designed to further explore the failures of visual attention induced by the cell phone conversation. In particular, the impaired recognition memory for the billboards in Experiment 2 may be due to a disruption in the visual-scanning pattern when participants were conversing on a cell phone. For example, McCarley et al. (2001) found that cell phone conversations interfered with the peripheral guidance of eye fixations to objects in static images of traffic scenes. Similarly, Harbluk et al. (2002) examined eye fixations in naturalistic driving and found a greater tendency to fixate directly ahead when conversing on a cell phone. It is conceivable that most, if not all of the recognition memory deficits observed in Experiment 2 were due to changes in visual-scanning patterns (i.e., reduced fixation on billboards in the dual-task conditions). However, an alternative interpretation is that the cell phone conversations reduce attention to objects even when drivers look directly at them. This latter interpretation would be consistent with Rumar's (1990) observation that a basic form of driver error is that drivers look at but do not see roadway traffic.

To differentiate between these various interpretations of the data, Experiment 3 measured eye fixations while participants performed the driving task conducted in Experiment 2. If the difference in recognition memory observed between single- and dual-task conditions in Experiment 2 is due to a difference in visual scanning, then this difference should be reduced or eliminated if memory is examined only for billboards that were fixated on by the participants. However, if the cell phone conversations reduce attention to fixated objects, then recognition memory for these billboards should be impaired in the dual-task condition relative to the single-task driving condition.

Method

Participants. Twenty undergraduates (15 men, 5 women) from the University of Utah participated in the experiment. Participants ranged in age from 18 to 23, with an average age of 20.6. All had normal or corrected-to-normal visual acuity, normal color vision (Ishihara, 1993), and a valid Utah driver's license. Each participant served in both single- and dual-task conditions. Of the 15 participants who reported that they owned a cellular phone, 80% reported that they used their phone while driving.

Stimuli and apparatus. The stimuli and apparatus were identical to Experiment 2, with the exception that eye movement data were recorded using an Applied Science Laboratories (ASL; Bedford, MA) eye and head tracker (Model 501). The ASL Model 501 eye tracker is a video-based unit

Table 4
Recognition Memory Performance for Experiment 3

Variable	Single task	Dual task	Control
No. of billboards classified as "old"	6.9 (0.5)	3.9 (0.6)	1.2 (0.5)
Fixation probability	0.66 (0.06)	0.62 (0.06)	
Fixation duration (msec)	1,122 (99)	1,009 (115)	
Conditional probability of recognition|billboard fixation	0.50 (0.05)	0.24 (0.04)	

Note. Standard errors appear in parentheses. No. = number.

that allows free range of head and eye movements, thereby affording naturalistic viewing conditions for the participant as they negotiated the driving environment.

Procedure. The procedure was identical to Experiment 2, with the exception that participants wore an ASL 501 eye tracker while performing the simulated driving task.

Analysis. Eye-tracking data were analyzed to determine whether the participant fixated on each billboard. The participant's eyes were required to be directed at the center of the billboard for at least 100 msec for the billboard to be classified as having been fixated. The 100-msec criterion was used to ensure that participants had time to attend to the stabilized image that fell on their retinas.

Results and Discussion

Table 4 presents the recognition memory data for Experiment 3. Perusal of the table indicates that the pattern of data obtained in Experiment 2 was replicated in Experiment 3. The classification of control billboards as "old" was infrequent, indicating a low base rate of guessing. Billboards presented in single-task conditions were correctly recognized more often than billboards from dual-task conditions, $t(19) = 4.53$, $p < .01$, $d = 1.3$. Recognition memory for billboards presented in dual-task conditions was also significantly above the guessing control, $t(19) = 4.04$, $p < .01$, $d = 1.2$, indicating that dual-task performance was significantly above guessing rates. Thus, these data replicated the finding that conversing on a cell phone impairs the recognition memory for objects encountered in the driving scene.

We next assessed whether the differences in recognition memory were due to differences in eye fixations on billboards. Overall, participants fixated on approximately two thirds of the billboards. However, the difference in the probability of fixating on billboards from single- to dual-task conditions was not significant, $t(19) = 0.76$, $p > .45$, $d = 0.16$. Given this small effect size, it is not surprising that a power analysis indicated that it would take over 150 participants for this effect to become significant. Thus, the contribution of this effect would appear to be minimal. We also measured total fixation duration in single- and dual-task conditions to ensure that the observed differences in recognition memory were not due to longer fixation times in single-task conditions. The difference in fixation duration between single- and dual-task conditions was also not significant, $t(19) = 0.75$, $p > .45$, $d = 0.23$. As mentioned previously, a power analysis indicated that it would require over 70 participants for an effect of this size to become significant, and even then, the contribution to the observed recognition memory performance would appear to be minimal. Thus, the differences in recognition memory performance that we observed in single- and dual-task conditions cannot be attributed to alterations in visual scanning of the driving environment.

We also computed the conditional probability of recognizing a billboard given that participants fixated on it while driving. This analysis is important because it specifically tests for memory of objects that were presented where the driver's eyes were directed (i.e., it would not be all that surprising to find impaired recognition memory for objects that were never looked at by the driver). The conditional probability analysis revealed that participants were more than twice as likely to recognize billboards presented in the single-task condition than in the dual-task condition, $t(19) = 4.53$, $p < .01$, $d = 1.4$. That is, when we ensured that participants fixated on a billboard, we found significant differences in recognition memory between single- and dual-task conditions. Even when the participant's eyes were directed at objects in the driving environment, they were less likely to remember them if they were conversing on a cellular phone.

We also performed a time-varying analysis of covariance (ANCOVA) in which recognition probabilities for those items that participants fixated on were statistically corrected for variations in fixation duration on a billboard-by-billboard basis. Consistent with the preceding analyses, the ANCOVA found significant differences in recognition memory between single- and dual-task conditions, $t(36) = 4.41$, $p < .01$, $d = 1.47$.[1] The ANCOVA-adjusted recognition probabilities were .47 and .22 for single- and dual-task conditions, respectively. Thus, our analyses indicate that cell phone conversations alter how participants attend to fixated information in the driving scene.

The results of Experiment 3 indicated that conversing on a cellular phone disrupts the driver's attention to the visual environment. Even when participants looked directly at objects in the driving environment, they were less likely to create a durable explicit memory of those objects if they were conversing on a cell phone. The data are consistent with the inattention-blindness hypothesis that the cell phone conversation disrupts performance by diverting attention from the external environment associated with the driving task to an engaging internal context associated with the cell phone conversation.

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[1] We tested both the homogeneity of variance and of regression assumptions underlying the ANCOVA analysis. Box's M was not significant, indicating that the assumption of homogeneity of variance was satisfied. A hierarchical-linear-modeling test for homogeneity of regression slopes was also not significant, indicating that the assumptions underlying the ANCOVA model were satisfied.

Experiment 4

Our final study was designed to further explore the apparent reduction in visual attention induced by cell phone conversations. In particular, Experiment 3 found that cell phone conversations reduce memory for fixated objects. We suggest that this is due to a suppression of the data-driven processing of the visual information in the driving environment. However, it is possible that the explicit tests of recognition memory used in Experiments 2 and 3 underestimated the total amount of information encoded during driving (e.g., Fernandez-Duque & Thornton, 2000; Hollingworth & Henderson, 2002; Hollingworth, Williams, & Henderson, 2001). To more thoroughly evaluate the inattention-blindness hypothesis, Experiment 4 measured the implicit perceptual memory for words that were presented at fixation during the pursuit-tracking task originally used by Strayer and Johnston (2001). We measured perceptual memory immediately after the tracking task, using a dot-clearing procedure in which words were initially masked by an array of dots and then slowly faded into view as the dots were gradually removed. We estimated the perceptual memory for an item by the amount of time participants took to correctly report the identity of that item.

Researchers using this dot-clearing procedure have found that words previously attended to are identified faster than new words and that these effects are long lasting (e.g., Feustel, Shiffrin, & Salasoo, 1983; Hawley & Johnston, 1991; Johnston, Dark, & Jacoby, 1985). We reasoned that if the cell phone conversations during driving reduce attention to fixated objects, then perceptual memory for foveally presented words should be impaired in dual-task conditions relative to single-task conditions. One advantage of the perceptual memory task is that it does not rely on the participant's explicit memory of objects in the driving scene. Indeed, evidence for implicit perceptual memory has been obtained even when observers have no explicit memory for old items (Johnston et al., 1985). Thus, the perceptual memory task is thought to provide an index of the initial data-driven processing of the visual scene.

To control for viewing conditions and exposure duration, we changed the simulated driving task from the high-fidelity driving simulator used in Experiments 1–3 to a pursuit-tracking task similar to that used by Strayer and Johnston (2001). The pursuit-tracking task provides greater experimental control at the expense of driving realism. These data, in conjunction with the findings obtained from Experiments 2 and 3, should provide converging evidence for the source of interference produced by cell phone conversations.

Method

Participants. Thirty undergraduates (17 men, 13 women) from the University of Utah participated in the experiment. Participants ranged in age from 18 to 25, with an average age of 19.6. All had normal or corrected-to-normal visual acuity, normal color vision (Ishihara, 1993), and a valid Utah driver's license. Each participant served in both single- and dual-task conditions.

Stimuli and apparatus. Participants performed a pursuit-tracking task, adapted from Strayer and Johnston (2001), in which they used a joystick to maneuver a cursor on a computer display to keep it aligned as closely as possible to a moving target. The target position was updated every 33 msec and was determined by the sum of three sine waves (0.07 Hz, 0.15 Hz, and 0.23 Hz). The target movement was smooth and continuous, yet essentially unpredictable. At intervals ranging from 10 to 20 s ($M = 15$ s), a four- to five-letter word, selected without replacement from the Kučera and Francis (1967) word norms, was presented for 500 msec at the location of the target. Each word subtended an approximate visual angle of 0.5° vertically and 2.0° horizontally. Altogether, 200 words were presented during the driving task, and an additional 100 words were presented as new words in the subsequent dot-clearing phase. A random assignment of words to conditions was generated for each participant. The latencies of responses in the dot-clearing phase were measured with millisecond precision by using a voice-activated response device, and response accuracy was manually recorded.

Procedure. The tracking portion of the study consisted of three phases. The single- and dual-task conditions were conducted following a warm-up interval that lasted 7 min and was used to acquaint participants with the tracking task. The single-task condition was conducted in two 7.5-min segments: one that immediately proceeded and one that immediately followed a 15-min dual-task segment. In the single-task segments, participants performed the tracking task by itself. In the dual-task segment, participants engaged in a cell phone conversation with a confederate and concurrently performed the tracking task. As in the preceding studies, the topic of conversation was determined by using a preexperimental questionnaire that assessed topics of interest for the participant. During the tracking task, words were presented for 500 msec at the center of fixation. Participants were asked to press a button on the joystick if the word was an animal name. Only 3% of the words were animal names, and these items were excluded from the dot-clearing phase of the experiment.

Immediately following the tracking task, participants performed the perceptual memory task. The dot-clearing procedure was used to measure the perceptual memory for old words, that is, those previously presented in the single- and dual-task conditions. New words that had not been previously presented were included to provide a baseline against which to assess perceptual memory for the old words. In the dot-clearing task, words were initially masked with random pixels, and the mask was gradually removed pixel by pixel until participants could report the identity of the word. A pixel from the mask was removed every 33 msec, rendering the word completely in view after 5 s. The words from the three categories (i.e., single task, dual task, and control) were presented in a randomized order in the dot-clearing phase of the study.

Results and Discussion

Table 5 presents the data from the dot-clearing phase of the study. Participants named old words from the single-task condition faster than control words, $t(29) = 4.97$, $p < .01$, $d = 0.34$, replicating prior demonstrations of implicit perceptual memory. Old words from the dual-task condition were also identified faster than control words, $t(29) = 2.31$, $p < .05$, $d = 0.18$. Most important, identification was slower for old words from the dual-task condition than those from the single-task condition, $t(29) = 2.39$, $p < .05$, $d = 0.14$. Although the effect size for this latter contrast is small, it is nevertheless of considerable theoretical importance (cf. Loftus, 1996; Rosenthal, Rosnow, & Rubin, 2000). These data indicated that cell phone conversations reduce percep-

Table 5
Implicit Perceptual Memory Performance for Experiment 4

Variable	Single task	Dual task	Control
Reaction time (msec)	3,114 (81)	3,176 (84)	3,252 (70)

Note. Standard errors appear in parentheses.

tual memory for items presented at fixation. Apparently, cell phone conversations reduce attention to external inputs, even of those presented at fixation.

General Discussion

Experiment 1 used a car-following paradigm and found that participants' reaction to a vehicle braking in front of them was impaired when they were conversing on a cell phone. Experiments 2–4 assessed an inattention-blindness interpretation of this impairment. Experiment 2 found that recognition memory for billboards presented in the driving environment was impaired when participants were conversing on a hands-free cell phone. Experiment 3 observed this impairment even for billboards on which participants directly fixated. Experiment 4 extended these findings by showing that implicit perceptual memory for words presented at fixation was impaired when participants were using a hands-free cell phone. In agreement with Strayer and Johnston (2001), the interference from cell phone use was obtained despite the fact that there was no manual manipulation of the phone during the dual-task portions of the experiments. Thus, these studies provide strong support for the inattention-blindness interpretation in which the disruptive effects of cell phone conversations on driving are due in large part to the diversion of attention from driving to the phone conversation.

Conversing on a cell phone appears to have altered the way that drivers attended to stimuli in the driving environment. These data extend our earlier observations of impaired detection and reaction to traffic signals (Strayer & Johnston, 2001) and sluggish reaction to brake lights (e.g., Experiment 1) when participants are engaged in cell phone conversations. We suggest that even when participants are directing their gaze at objects in the driving environment that they may fail to "see" them because attention is directed elsewhere (see also Rumar, 1990).

This indication of cell phone-induced inattention blindness extends laboratory-based demonstrations of apparent failures of visual attention to the driving domain (e.g., Mack & Rock, 1998; Neisser, 1979; Rensink, Oregan, & Clark, 1997; Simons & Chabris, 1999). However, one important difference between these earlier studies and our present work is that the former involved the presentation of simultaneous (and often overlapping) visual images, whereas our research involved the combination of visual (i.e., the driving environment) and auditory (i.e., the cell phone conversation) information. This suggests that the locus of the effect is at a central attentional level and not due to structural interference or overload of a perceptual or response channel. As such, these data would appear to be at odds with models of divided attention that suggest that a cell phone conversation, an auditory–verbal–vocal task, can be successfully timeshared with driving, a visual–spatial–manual task (Wickens, 1984; but see Wickens, 1999). Moreover, our studies extend the inattention-blindness effect to the performance of more dynamic, engaging, and naturalistic environments than the more typical passive viewing of videotapes or computer displays.

Further, our research demonstrates that conversations on a hands-free cell phone impair both explicit recognition memory of billboards and implicit perceptual memory of words presented at fixation. Because the implicit perceptual memory effects do not rely on explicit recollection, they offer a more direct assessment of the data-driven processing of objects presented at fixation while driving. The reduction in the data-driven processing of the driving environment provides a good account for why drivers' responses are often sluggish in response to unexpected events encountered while driving (see also Rumar, 1990). It is also interesting to note that the reduction of data-driven processing occurred for stimuli that appeared as sudden onsets, which are often thought to capture attention automatically (Yantis, 1993; Yantis & Jonides, 1990). Thus, these data suggest that cell phone conversations interfere with the automatic attention-capturing properties of sudden onset stimuli occurring in the driving environment.

It is worth considering how well the impaired recognition memory for billboards generalizes to other stimuli in the driving environment. For example, researchers may argue that when drivers engage in cell phone conversations, they attempt to strategically reallocate attention from the processing of less relevant information in the driving scene (e.g., billboards) to the cell phone conversation while continuing to give highest priority to the processing of task-relevant information in the driving scene (e.g., the car in front of them). However, the eye-tracking data from Experiment 3 did not provide support for this interpretation because participants looked at billboards equally often in single- and dual-task conditions. Indeed, the data from Experiments 2–4 provide clear evidence that there was a reduction in the processing of information, falling directly into the line of gaze when participants were conversing on a cell phone. Furthermore, any reasonable account of task relevance would have to include attending to the vehicle immediately in front of the driver. Nevertheless, the car-following paradigm used in Experiment 1 found significant impairments in driving performance when participants were conversing on a hands-free cell phone. If participants were attempting to focus on more task-relevant information in the driving scene, then this strategy proved to be inadequate because dual-task interference was observed even with task-relevant information in the driving scene. We suggest that the most straightforward interpretation of the dual-task deficits in explicit memory observed in the billboard studies (Experiments 2 and 3), in implicit memory observed in the dot-clearing study (Experiment 4), and in reaction to a car braking in front of the driver in the car-following study (Experiment 1) is that attention was diverted from the visual scene immediately associated with driving (of both higher and lower relevance) to the cell phone conversation. Although we cannot rule out the possibility that the dual-task deficits may be greater for stimuli of lower relevance, we note that for practical implications the interference produced by cell phone conversations is apparent for stimuli that are, in fact, immediately associated with safe driving (e.g., reacting appropriately to traffic signals and brake lights).

A comment on the nature of our cell phone conversations is also appropriate. Unlike earlier research using working memory tasks (Alm & Nilsson, 1995; Briem & Hedman, 1995), mental-arithmetic tasks (Harbluk et al., 2002; McKnight & McKnight, 1993), reasoning tasks (I. D. Brown et al., 1969), or conversations concerning semicontroversial topics (Strayer & Johnston, 2001), the conversations in our present study were designed to be naturalistic casual conversations centering on topics of interest to the participant. As would be expected with any naturalistic conversation, they were unique to each participant. The task of the confederate in our studies was to maintain a dialog in which the participant listened and spoke in approximately equal proportions. However, given that our cell phone conversations were casual, they probably underestimated the impact of intense business negotiations or other emotional conversations conducted over the phone. Interestingly, Hahn et al. (2000) conducted a cost–benefit analysis that attempted to justify the use of cell phones while driving in terms of the impact on business productivity. Although it remains to be determined how different types of cell phone conversation affect driving, our studies demonstrate that casual, naturalistic, hands-free cell phone conversations do produce significant interference.

It is also worth considering how cell phone conversations compare with other auditory–verbal activities that may be performed while driving. In our earlier studies (Strayer & Johnston, 2001), we found that listening to radio broadcasts or to books on tape did not interfere with the reaction to simulated traffic signals, whereas both handheld and hands-free cell phone conversations impaired participants' detection and reaction to these signals. Similarly, McCarley et al. (2001) found the detection of changes in real-world traffic scenes was impaired when participants were conversing on a hands-free cell phone; however, no such performance decrements were observed when participants listened to prerecorded conversations from other participants. Moreover, our earlier study (Strayer & Johnston, 2001) found that a simple shadowing task did not lead to impairments in simulated driving; however, when the shadowing task became more cognitively involved, impairments in performance were observed. Together, these findings suggest that neither attending to auditory input nor producing vocal outputs, by themselves, are sufficient to produce impairments in driving performance. Rather, active engagement in the cell phone conversation appears to be necessary to produce interference with driving. Lee et al. (2001) has recently extended these findings by showing that active interaction with a speech-based e-mail system can also impair drivers' reactions.

By contrast, a conversation with a passenger in the vehicle is often qualitatively different from conversations on a cell phone (Strayer & Johnston, 2001; see also Direct Line Motor Insurance, 2002). In the former case, both the driver and the passenger are aware of the driving conditions and often modulate their conversation on the basis of the real-time demands of driving. In the latter case, such modulation is more difficult because the person conversing with the driver is unaware of the real-time driving demands. However, further research is clearly needed that examines how the nature and intensity of the conversation impacts driving.

We also observed in debriefing that about half the participants commented that they found it no more difficult to drive while using a cell phone than to drive without using a cell phone. These participants reported that they have observed others driving erratically while using a cell phone, but these participants rarely, if ever, thought that their own driving was impaired when they used the cell phone. Thus, there appears to be a disconnect between the self-perception of one's driving performance and objective measures of their driving performance. Indeed, our data also indicate that drivers are not processing the data-driven information that would provide evidence that their driving is impaired while using a cell phone. That is, a consequence of using a cell phone is that it may make drivers insensitive to their own impaired driving behavior.

Finally, it is important to consider the real-world risks associated with conversing on a cell phone while driving. Experiment 1 indicated that the interference produced by cell phone conversations on simulated driving is significant and that the overall effect size is medium to large (e.g., 0.74). There are other ways to estimate the risks associated with this dual-task activity. For example, high-fidelity driving simulator studies (Direct Line Motor Insurance, 2002; Strayer, Drews, & Crouch, 2003) controlling for time on task and driving conditions found that participants' driving performance was more impaired when they were conversing on a cell phone than when they were legally intoxicated. Redelmeier and Tibshirani (1997) provided another important source of evidence concerning the association between cell phone use and motor vehicle accidents. In their study, the cellular phone records of 699 individuals involved in motor vehicle accidents were evaluated. These authors found that cell phone use was associated with a four-fold increase in the likelihood of getting into an accident and that this increased risk was comparable to that observed when driving with a blood alcohol level at the legal limit. Taken together, these observations provide converging evidence indicating that conversing on a cell phone while driving poses significant risks both to the driver and to the general public.

In summary, we suggest that the use of cellular phones disrupts performance by diverting attention toward an engaging cognitive context other than the external environment immediately associated with driving. Our data further suggest that legislative initiatives that restrict handheld devices but permit hands-free devices are not likely to eliminate the problems associated with using cell phones while driving because these problems are attributed in large part to the distracting effects of the phone conversations themselves, effects that appear to be due to the direction of attention away from the external environment and toward an internal cognitive context associated with the phone conversation.

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