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Research Report

A decrease in brain activation associated with driving when listening to someone speak

Marcel Adam Just*, **Timothy A. Keller**, **Jacquelyn Cynkar**

Center for Cognitive Brain Imaging, Department of Psychology, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

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ABSTRACT

Behavioral studies have shown that engaging in a secondary task, such as talking on a cellular telephone, disrupts driving performance. This study used functional magnetic resonance imaging (fMRI) to investigate the impact of concurrent auditory language comprehension on the brain activity associated with a simulated driving task. Participants steered a vehicle along a curving virtual road, either undisturbed or while listening to spoken sentences that they judged as true or false. The dual-task condition produced a significant deterioration in driving accuracy caused by the processing of the auditory sentences. At the same time, the parietal lobe activation associated with spatial processing in the undisturbed driving task decreased by 37% when participants concurrently listened to sentences. The findings show that language comprehension performed concurrently with driving draws mental resources away from the driving and produces deterioration in driving performance, even when it does not require holding or dialing a phone.

1. Introduction

An enduring question about the human mind concerns the ability to do two things at the same time. As technological and informational capabilities of our environment increase, the number of available information streams increases, and hence the opportunities for complex multitasking increase. In particular, multitasking of driving and conversing on a cell phone is technologically available, but intuitively seems dangerous in some circumstances. Although driving becomes sufficiently cognitively automated (Schneider, 1999) to permit experienced drivers to perform other tasks at the same time, such as carrying on a conversation, a large number of behavioral studies have now shown that performing another cognitive task while driving an actual or virtual car substantially degrades driving performance (Alm and Nilsson, 1994, 1995; Anttila and Luoma, 2005; Beede and Kass, 2006; Brookhuis et al., 1991; Consiglio et al., 2003; Drory, 1985; Engström et al., 2005; Haigney et al., 2000; Hancock et al., 2003; Horberry et al., 2006; Horrey and Wickens, 2004; Hunton and Rose, 2005; Jamson and Merat, 2005; Kubose et al., 2006; Lamble et al., 1999; Lesch and Hancock, 2004; Liu and Lee, 2005; Matthews et al., 2003; McKnight and McKnight, 1993; Patten et al., 2004; Ranney et al., 2005; Recarte and Nunes, 2000, 2003; Santos et al., 2005; Shinar et al., 2005; Strayer and Drews, 2004, 2007; Strayer et al., 2003, 2006; Strayer and Johnston, 2001; Törnros and Bolling, 2005, 2006; Treffner and Barrett, 2004). Although some of these studies show that some aspects of driving are unaffected by a secondary task (e.g., Haigney et al., 2000) and in some cases certain aspects improve (e.g., Brookhuis et al., 1991; Engström et al., 2005), a recent meta-analysis of the literature suggests a large overall decrement in driving performance when a secondary task is added (Horey and Wickens, 2006).

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* *Corresponding author*. Fax: +1 412 268 2804.
E-mail address: just@cmu.edu (M.A. Just).

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Public concern about the effect of distraction on driving has led to legislation in some areas that limits the use of cellular phones while driving. The motivation for such legislation may initially have been concern about interference caused by holding and dialing a cellular phone, and early studies suggested that the manual aspects of cellular phone use were the critical determinant of a decrement in driving performance (Drory, 1985). However, recent behavioral studies have shown that simulated driving performance is also disrupted by conversations using hands-free devices (Alm and Nilsson, 1994, 1995; Anttila and Luoma 2005; Beede and Kass, 2006; Brookhuis et al., 1991; Consiglio et al., 2003; Horberry et al., 2006; Hunton and Rose, 2005; Jamson and Merat 2005; Lamble et al., 1999; Levy et al., 2006; Liu and Lee, 2005; Matthews et al., 2003; Patten et al., 2004; Ranney et al., 2005; Shinar et al., 2005; Strayer and Drews, 2004; Strayer et al., 2003, 2006; Strayer and Johnston, 2001; Törnros and Bolling, 2005, 2006; Treffner and Barrett, 2004), and epidemiological studies of real-world accidents suggests that users of hands-free phones are just as likely to have an accident as users of hand-held devices (Redelmeier and Tibshirani, 1997; McEvoy et al., 2005). In their meta-analysis of recent dual-task driving studies, Horey and Wickens (2006) concluded that the costs to driving performance resulting from a secondary simulated conversation task were equivalent for hand-held and hands-free devices. Such findings suggest that the deterioration in driving performance resulting from cellular phone usage results from competition for mental resources at a central cognitive level rather than at a motor output level, and that legislative measures which simply restrict drivers to the use of hand-free phones fail in their intent to limit an important distraction to driving.

The consequences of multitasking on brain activation have been examined in several previous neuroimaging studies. It is important to distinguish, however, between rapidly switching between two tasks versus the situation on which this paper focuses, namely, performing two tasks concurrently. In the case of task switching, activation in dorsolateral prefrontal cortex *increases* in the dual-task case relative to the single-task case, presumably due to the increased demand on prefrontal executive processes that coordinate the performance of the two tasks (Braver et al., 2003; D'Esposito et al., 1995; Dreher and Grafman, 2003; Dux et al., 2006; Szameitat et al., 2002). However, the results are different for tasks that involve two concurrent streams of thought. The activation in the regions that are activated by each of the tasks when they are performed alone typically *decreases* from the single task to the concurrent dual-task situation, presumably because of the competition for the same neural resources (Klingberg and Roland, 1997; Rees et al., 1997; Vandenberghe et al., 1997). Moreover, the rostral anterior cingulate becomes involved in concurrent dual tasks (Dreher and Grafman, 2003).

Of particular interest here is the finding that there seems to be a limit on the overall amount of brain activation in a concurrent dual-task situation, even if the two tasks draw on *different* cortical networks. In a study of mental rotation and sentence comprehension tasks that were performed in isolation or concurrently, the activation volume in these non-overlapping regions associated with each task was substantially less when the tasks were performed together than the sum of the activation volumes when the two tasks were performed separately (Just et al., 2001). In other words, each component task evoked much less cortical activity when it was performed concurrently with another task than when performed alone, even though the two tasks drew on different regions. This finding has been replicated in an experiment in which the auditory and visual stimuli were presented in each of the three conditions, and only the participants' attention to one, the other, or both tasks was manipulated (Newman et al., 2007). These results suggest that two concurrently-performed complex tasks draw on some shared, limited resource, and thus the resources available for performing each component task are diminished in the concurrent situation relative to when the task is performed alone. This interpretation is consistent with the notion that there is a fundamental constraint that limits the ability to drive and process language at the same time. We will later offer a suggestion concerning the type of resource constraint that may be limiting such concurrent dual-task performance.

Although no previous study has assessed the neural effect of a second task on driving, a recent study did assess the effect of performing a simple visual detection task on a passive viewing of a realistic video-taped driving scenario (Graydon et al., 2004). This study found decreased activation in the dual-task relative to the single-task passive viewing condition in several frontal areas (left superior frontal gyrus, the left orbital frontal gyrus, and the right inferior frontal gyrus). The frontal decrease in activation in the presence of a secondary visual task suggests a limitation on the resources available for processing driving-related visual information, at least in this case of two visual tasks, a simple visual detection task performed during the passive viewing of a driving scenario.

Here we report for the first time the findings from a study using brain imaging to investigate the effects of performing an auditory language comprehension task while simultaneously performing a simulated driving task, two tasks known to draw on different cortical networks[1]. Several previous neuroimaging studies of driving (in a single-task situation) have indicated the feasibility of measuring brain activity during simulation driving in an MRI scanner (Calhoun et al., 2002; Walter et al., 2001). Participants were scanned at 3 Tesla with a blood-oxygenation level dependent fMRI acquisition sequence while they maneuvered a virtual car in a driving simulator (see Fig. 1). They steered the car using a trackball or mouse in their right hand along a winding virtual road at a fixed speed that made the task moderately difficult. In the dual-task condition, participants not only steered but also listened to general knowledge sentences and verified them as true or false using response buttons held in their left hand. Behavioral performance on the comprehension task was assessed in terms of reaction time and response accuracy; performance in the simulated driving task was assessed in terms of road-maintenance errors (hitting the berm) and measurement of the deviation of the path taken from an ideal

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[1] Normal driving itself can be considered a multi-task, requiring the integration of information not only from multiple visual inputs (e.g., the road ahead, the rear-view mirror, the instrument display) and other sensory modalities (e.g., the sound of other vehicles and proprioceptive information about the stability of the vehicle on the road), as well as the coordination of multiple behavioral outputs (e.g., steering, braking, acceleration). In the present study we have simplified the driving task by requiring only some of the key components of driving, namely the maintenance of the heading of a vehicle on the basis of information based on the processing of a visual display of the road ahead.

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Fig. 1 – Screen capture of the display for the driving simulation. Participants steered the vehicle with a computer mouse or trackball held in their right hand under two conditions; one in which they focused attention on the driving task alone, and one in which they also judged whether auditorily presented sentences describing world knowledge were true or false. Blocks of the driving alone and driving while listening conditions were 60-s in duration and were alternated with 24-s fixation baseline intervals.

path (lane maintenance). The analyses mapped the areas that showed reliable activation at the group level for each of the conditions relative to a baseline fixation task, and the areas that showed reliable differences in activation between the two conditions. In addition, the amount of activation in the single task and dual-task conditions (assessed as the mean percentage change in signal intensity in pre-defined anatomical areas for each participant) was directly compared. If the auditory comprehension task draws attentional resources away from the task of driving, then one should expect increased errors in driving and less driving-related activation in the presence of a concurrent comprehension task.

2. Results

The central findings were that the sentence listening task reliably degraded driving performance, and in addition, it resulted in decreases in activation in key regions that underpin the driving task, as further quantified below.

2.1. *Behavioral measures*

Participants performed the sentence comprehension task at a 92% accuracy level (SD=0.06%), confirming that they were attending to the auditory stimuli in the driving with listening condition. The behavioral measures indicated reliably more road-maintenance errors and larger root mean squared (RMS) deviation from an ideal path in the driving with listening condition. Mean road-maintenance errors (hitting the berm) increased from 8.7 (SD=9.7) in the driving-alone condition to 12.8 (SD=11.6) in the driving while listening condition ($t(28)=2.22$, $p<.05$). The mean RMS deviation from the ideal path increased from 2.48 to (SD=0.51) in the driving-alone condition to 2.64 (SD=0.56) in the driving while listening condition ($t(28)=2.79$, $p<.01$). Both of the measures of driving accuracy are essentially continuous visuo-spatial tracking measures rather than reaction time measures of hazard avoidance. A meta-analysis (Horey and Wickens, 2006) of 16 behavioral studies of

A. Driving Alone

B. Driving with Listening

Fig. 2 – Whole-brain voxel-wise random-effects statistical parameter maps of each condition contrasted with the fixation baseline thresholded at $p<.0001$ with an 81-voxel extent threshold (resulting in a cluster-level threshold of $p<.05$ after correction for multiple comparisons). Similar areas of activation are present in both conditions but with additional language-related activity in temporal and inferior frontal areas (yellow ovals).

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dual-task driving concluded that the costs associated with cell phone conversations are even larger for reaction time tasks than for tracking tasks, so our study may be underestimating the behavioral impact of a secondary task on driving.

2.2. *Functional imaging measures*

Group-level random-effects analysis indicated that the driving task when performed alone produced large areas of activation (compared to fixation) in bilateral parietal and occipital cortex, motor cortex, and the cerebellum, as shown in Fig. 2A. Three clusters of activation survived correction for multiple comparisons ($p < .05$). The largest cluster (39,504 voxels) had its peak activation in the left supplementary motor area (t(28) = 12.00, at Montreal Neurological Institute (MNI) coordinates −6, −18, 64), but the activation extended to left and right primary motor areas, the left and right parietal lobe, the left and right occipital lobe, and into bilateral regions of the cerebellum. A second cluster (1791 voxels) had a peak in the left thalamus (t(28) = 8.72 at MNI coordinates −14, −22, 2) but extended into other left subcortical structures including the putamen, pallidum, caudate, and hippocampus, and also left cortical areas of the insula, inferior frontal gyrus, and middle frontal gyrus. The final cluster (429 voxels) had its peak in the right hippocampus (t(28) = 7.71 at MNI coordinates 22, −30, −8) and extended into the right thalamus, and right cortical areas of the parahippocampal and lingual gyri.

When sentence listening was combined with the driving task, the same network of driving-related areas were activated, as shown in Fig. 2B. For the contrast between driving with listening and the fixation baseline, the largest cluster of activation (47,911 voxels) had a peak in the right middle occipital gyrus (t(28 = 12.43 at MNI coordinates 28, −96, 4) but extended to the same areas found in the contrast of driving alone with fixation; left and right supplementary and primary motor areas, left and right parietal lobes, left and right occipital lobes, and bilateral areas of the cerebellum. As expected, the addition of the listening task gave rise to activation in additional areas that underpin the sentence processing task, namely bilateral temporal and left inferior frontal regions. The largest cluster of activation extended into the left inferior frontal gyrus, and also into the left temporal language area (see the left panel of Fig. 2B). In addition, a cluster of 3022 voxels was reliably active in the homologous region of the right temporal lobe (peak t(28) = 10.99 at MNI coordinates 50, −24, −6). A final small cluster of activation (185 voxels) was found in the right frontal lobe with a peak in the middle frontal gyrus (t(28) = 6.14 at MNI coordinates 24, 52, 6).

If processing spoken language draws attentional/brain resources away from the task of driving, one would expect a decrease in activation in the brain areas that underpin the driving task. The findings clearly supported this prediction. Informal comparison of Fig. 2A and B suggests that the driving-related activation in bilateral parietal cortex decreased with the addition of the sentence listening task. Direct random-effects statistical comparison of the driving-alone condition with the driving with listening condition confirms this suggestion (see Fig. 3 and Table 1). A number of bilateral occipital

A. Driving Alone minus Driving with Listening

B. Driving with Listening minus Driving Alone

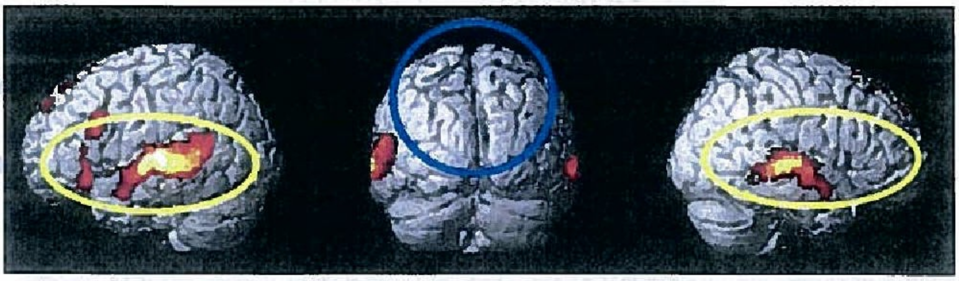

Fig. 3 – Whole-brain voxel-wise random-effects statistical parameter maps of direct contrasts between the two conditions thresholded at $p < .0001$ with an 81-voxel extent threshold (resulting in a cluster-level threshold of $p < .05$ after correction for multiple comparisons). The top panel indicates that parietal and superior extrastriate activation *decreases* with the addition of a sentence listening task (blue circle). The bottom panel shows that the addition of a sentence listening task results in activation in temporal and prefrontal language areas (yellow ovals).

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Table 1 – Areas of greater activation for Driving Alone than Driving with Listening

Location of peak activation	Cluster size	t(28)	MNI coordinates		
			x	y	z
L supramarginal gyrus	166	7.13	−56	−36	36
R superior parietal lobe	2020	6.8	10	−82	52
L superior parietal lobe	139	5.8	−28	−54	58
L inferior parietal lobe	154	5.55	−34	−42	38
L superior occipital gyrus	182	5.49	−26	−88	26

Note: Cluster size is in 2×2×2 mm voxels. L = left, R = right.

and parietal areas showed greater activation in the driving-alone condition relative to the same condition performed with the sentence listening task, as shown in Fig. 3A and in Table 1. As expected, driving with listening resulted in more activation than driving alone in bilateral temporal language areas and the left inferior frontal gyrus, as shown in Fig. 3B and in Table 2. There was also greater activation in the right supplementary motor area in this contrast, possibly due to the addition of the requirement to respond to the sentence comprehension task with the left hand.

Anatomical regions of interest (ROIs) defined *a priori* were used to directly compare the activation levels (percentage change in signal intensity relative to fixation) in the two conditions. There were large, reliable decreases in areas involved in the spatial processing associated with driving. The decrease from single to dual task was 37% for the spatial areas ($F(1, 28) = 29.38$, $p < .0001$. Table 3 shows the mean percentage change in signal intensity for each of the anatomically-defined regions of interest examined in the driving alone and driving with listening conditions. Most of the parietal areas associated with spatial processing individually showed a reliable decrease in activation when the sentence comprehension task was added, with the largest decreases found in the right parietal lobe. Table 3 also groups the anatomical areas based on function, and Fig. 4 aggregates the results for each of these groupings. As shown in Fig. 4, the spatial areas show a large decline in activation in driving with listening compared to driving alone; the visual, motor, and executive areas show no reliable decrease; and the language areas show a large increase.

Although the visual areas show a trend toward a decrease in activation between the driving-alone condition and the driving with listening condition, this decrease was not reliable for any of the areas considered individually or for the aggregate measure of visual activation. However, more superior areas of the right and left occipital lobe did show significantly less activation for the driving with listening condition in the voxel-wise whole brain contrasts (see Fig. 3A). These areas have been grouped with the spatial processing areas in Table 3 and Fig. 4, due to their proximity to the parietal lobes and their role in the dorsal visual stream, but this grouping is perhaps somewhat arbitrary. The data indicate that while

Table 2 – Areas of greater activation for Driving with Listening than Driving Alone

Location of peak activation	Cluster size	t(28)	MNI coordinates		
			x	y	z
L middle temporal gyrus	4552	10.87	−56	−12	−6
Right superior temporal gyrus	2523	9.82	50	−20	4
L inferior frontal gyrus	497	9.33	−44	20	26
R supplementary motor	1055	7.00	2	24	62

Note: Cluster size is in 2×2×2 mm voxels. L = Left, R = right.

Table 3 – Mean percentage change in signal intensity in anatomical regions of interest (ROI)

Region of interest	Driving alone		Driving with listening	F(1, 28)
Spatial areas				
L intraparietal sulcus	0.315	>	0.231	8.14*
R intraparietal sulcus	0.400	>	0.267	14.28**
L inferior parietal lobe	0.461	>	0.348	5.67*
R inferior parietal lobe	0.083		0.011	3.64
L superior parietal lobe	0.239	>	0.158	10.23*
R superior parietal lobe	0.226	>	0.120	14.01**
L superior extrastriate	0.337	>	0.234	6.63*
R superior extrastriate	0.374	>	0.246	9.25*
All spatial areas	0.258	>	0.163	29.38**
Visual sensory/perceptual areas				
Calcarine sulcus	0.189		0.143	1.56
L inferior extrastriate	0.267		0.216	1.52
R inferior extrastriate	0.306		0.244	2.66
L inferior temporal lobe (pos)	0.138		0.108	0.17
R inferior temporal lobe (pos)	0.179		0.109	1.20
L inferior temporal lobe (mid)	0.111		0.140	0.05
R Inferior Temporal lobe (mid)	0.149		0.129	0.02
All visual areas	0.191		0.156	1.39
Motor/pre-motor areas				
Supplementary motor area	0.212		0.244	1.73
L precentral gyrus	0.429		0.380	1.68
R precentral gyrus	0.222		0.196	0.76
All motor areas	0.288		0.273	0.32
Executive function areas				
L middle frontal gyrus	0.108		0.092	0.23
R middle frontal gyrus	0.113		0.076	1.34
Anterior cingulated	−0.085		−0.096	0.18
Superior medial frontal	−0.085		−0.096	0.18
All executive areas	0.035		0.030	0.07
Language areas				
L ant. superior temporal gyrus	0.043	<	0.399	42.45**
R ant. superior temporal gyrus	0.076	<	0.391	21.95**
L pos. superior temporal gyrus	−0.024	<	0.214	37.98**
R pos. superior temporal gyrus	−0.012	<	0.077	4.29*
L pars triangularis	0.114	<	0.256	12.64**
R pars triangularis	0.081	<	0.161	6.01*
L pars opercularis	0.136		0.178	1.36
R pars opercularis	0.180		0.167	0.18
L insula	0.074		0.090	0.21
R insula	0.036		0.027	0.07
All language areas	0.070	<	0.196	64.43**

Note: inequality signs indicate the direction of a statistically reliable difference between Driving Alone and Driving with Sentence Listening. L = left, R = right. *=$p<.05$ uncorrected, **=$p<.05$ Bonferroni corrected for the number of regions of interest examined.

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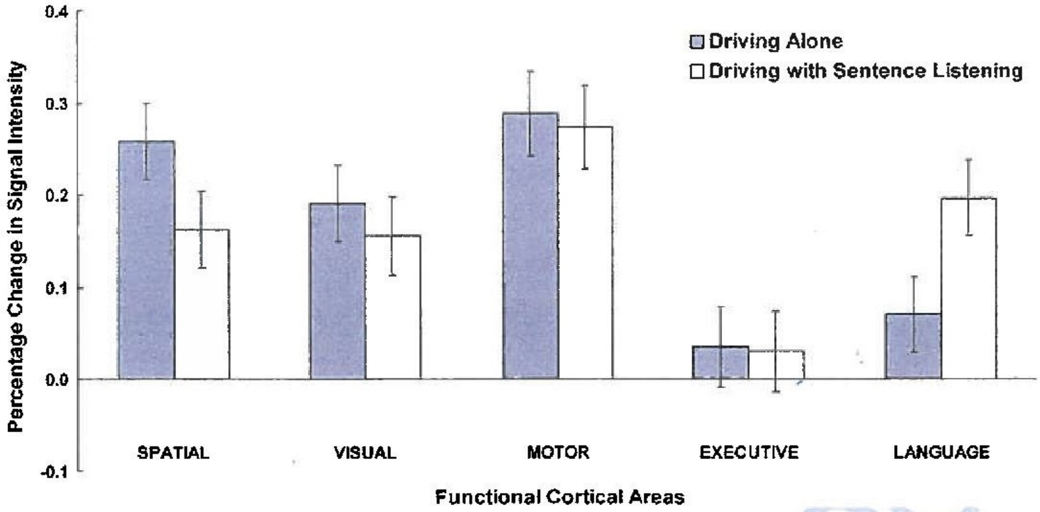

Fig. 4 – The percentage change in signal intensity for five functional groupings (networks) of cortical areas. The component regions of each network are those specified in Table 3. The driving-related activation in spatial processing areas significantly decreases with the addition of the sentence listening task. The addition of the sentence listening task significantly increases language area activation. Error bars show the standard error of the mean.

primary visual areas show no effect of the multitasking in this study, some secondary visual areas do decrease their activation.

In frontal areas associated with executive function, including dorsolateral prefrontal cortex and anterior cingulate, one might expect that the need to coordinate the processing in the two tasks would lead to increased activation, as D'Esposito et al. (1995) reported. However, note the previous distinction between performing two tasks concurrently (such as driving and sentence listening) versus rapidly switching between two tasks (such as the dual tasks studied by D'Esposito et al., 1995). Unlike the findings of increased activation in prefrontal areas for task switching, these prefrontal regions showed an equivalent percentage change in signal intensity for the driving alone and driving concurrently with sentence listening conditions. This finding indicates that not all multitasking requires additional executive functioning.

As expected, there was an overall increase in the percentage change in signal intensity in language areas when the comprehension task was added to the driving task. This increase was prominent in bilateral primary and secondary auditory areas of the temporal lobe and in the pars triangularis region of Broca's area in the left hemisphere and the homologous region of the right hemisphere, as indicated in Table 3. There was a slight trend toward a greater percentage change in signal in left pars opercularis, consistent with the results of the voxel-wise analysis, but not in right pars opercularis.

The finding of decreased parietal activation for the driving with listening condition was also found when the volume of activation rather than the percentage change in signal intensity was considered. For this analysis, the number of voxels reliably activated in the a priori spatial anatomical ROIs was computed for each participant at $t > 4.90$ (corresponding to a within-participant height threshold of $p < 0.05$, corrected for multiple comparisons) for the contrast of each condition with the fixation baseline. In the spatial areas, as identified in Table 3, the mean total number of activated voxels decreased from 1653 ($SE = 103$) to 1195 ($SE = 103$) from the driving-alone condition to the driving with listening condition, ($F(1, 28) = 41.65$, $p < .0001$).

3. Discussion

The new findings clearly establish the striking result that the addition of a sentence listening task decreases the brain activation associated with performing a driving task, despite the fact that the two tasks draw on largely non-overlapping cortical areas (Just et al., 2001; Newman et al., 2007). Activation decreased when the listening comprehension task was added to the driving task in bilateral parietal and superior extrastriate secondary visual areas. These areas have been shown to activate when simulated driving is contrasted with a passive viewing task in previous studies (Calhoun et al., 2002). The parietal areas which show a decrease here have been implicated in not only the types of spatial processing associated with driving, but also in the allocation of visual spatial attention (Rushworth et al., 2001). The decreased parietal activation in the dual-task condition may therefore be a reflection of both a decrease in the spatial computations associated with driving as well as a decrease in spatial attention. Converging evidence comes from an ERP study of simulated driving, in which the amplitude of the P300, which was maximal over the parietal electrodes (likely reflecting stimulus encoding), was reduced by 50% in a dual-task condition as compared to a driving-alone condition (Strayer and Drews, 2007). These brain activation findings provide a biological account for the deterioration in driving performance (in terms of errors and lane maintenance) that occurs when one is also processing language.

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We offer the following interpretation of the main findings, expressed in terms of the underlying neural systems. The results are consistent with the hypothesis, derived from previous behavioral studies, that a simulated cellular telephone conversation disrupts driving performance by diverting attention from the driving task. We interpret this diversion of attention as reflecting a capacity limit on the amount of attention or resources that can be distributed across the two tasks. This capacity limit might be thought of as a biological constraint that limits the amount of systematic neural activity that can be distributed across parts of the cortex. The specific biological substrate that imposes the capacity limitation is not currently known; it could be, for example, the biochemical resources underpinning the neural activity, or it could be the communication bandwidth underpinning the inter-region cortical communication. Whatever the biological source of the constraint, the findings suggest that under mentally demanding circumstances, it may be dangerous to mindlessly combine the special human capability of processing spoken language with a more recent skill of controlling a large powerful vehicle that is moving rapidly among other objects.

Besides this critical practical application, the study makes a number of other interesting points that illuminate the nature of multitasking. For example, although one might have thought that multitasking would make special demands on executive processes that coordinate the performance of two tasks simultaneously, there was in fact no increase in activation from the single- to dual-task in the prefrontal areas commonly associated with executive function. This replicates a previous result that was obtained when the comprehension task used here was combined with a mental rotation task (Just et al., 2001; Newman et al., 2007). Other imaging studies have also failed to find additional frontal areas specifically involved in dual-task performance (Adcock et al., 2000; Bunge et al., 2000; Goldberg et al., 1998; Klingberg, 1998), although there is also ample evidence that for some combinations of tasks, prefrontal activation does increase in the dual-task situation (D'Esposito et al., 1995; Szameitat et al., 2002; Dreher and Grafman, 2003; Loose et al., 2003). The main determinant of whether or not multitasking is demanding of executive function may depend on how automatic the two tasks are in the first place and whether they draw on non-overlapping cortical areas. Both tasks examined here, simulated driving and auditory comprehension, are relatively automatic, in that they draw very little on executive functions and evoke little frontal activation when performed alone. When these two tasks are combined as two streams of thought, no additional executive functioning/activation occurs. One might expect central executive processes to eventually become engaged in real-world driving during a cell phone conversation if a driving emergency arises; however, the latency of the executive processes (how soon the executive areas become activated) would be expected to be longer in the dual-task situation.

In primary visual areas (the occipital pole and the calcarine sulcus), there was no reliable change in the amount of activation when the comprehension task was added to driving. The differential effect of a concurrent task on primary versus secondary visual processing areas is consistent with eye-movement data suggesting that a concurrent task decreases foveal attention to visual information in driving without altering the pattern of fixations that the driver makes (Strayer et al., 2003), an impairment in driving performance caused by a concurrent task referred to as "inattention blindness." The new fMRI results here suggest that although the oculomotor activity may remain similar when a concurrent task is added to driving, preserving the visual input to primary sensory areas, the processing carried out in secondary visual areas is diminished. We note, however, that other studies of divided attention between visual and auditory tasks have shown decreased primary visual activation in the divided attention condition (Loose et al., 2003) and our earlier study combining mental rotation with listening comprehension also found a decrease in activation in primary visual areas for the dual-task condition relative to performing the mental rotation task alone (Just et al., 2001). The effect of a concurrent auditory task on primary visual areas may depend on the automaticity of the visual task, with there being less impact on a more automatic task, such as driving, and more impact on a strategically controlled task, such as mental rotation.

Unlike cell phone conversations, our sentence listening task did not require the participants to speak, and is thus probably less disruptive to driving than a full fledged conversation might be. Recarte and Nunes (2003) found that simply requiring participants to attend to auditory messages did not alter visual search or behavioral performance relative to driving alone, but that tasks involving speech production did affect both eye-movements and behavioral performance. Strayer and Johnston (2001) found that simply listening to speech and even actively shadowing it did not disrupt driving performance, but that a verb generation task did cause disruption. Horey and Wickens (2006) analyzed the combined effect size for 15 experiments involving a real conversation and 22 experiments that used various information processing tasks designed to simulate some of the demands of conversation. The effect of both types of tasks were significant in producing errors in driving performance, although the costs were higher for actual conversation than for other information processing tasks. It is therefore likely that our comprehension task underestimates the decrease in driving-associated activation and the deterioration of driving performance that would result from actual cell phone conversations.

Another limitation of the current study is that participants did not perform the sentence comprehension task in isolation. The inclusion of such a single-task sentence listening condition in future neuroimaging studies of multi-tasking while driving would permit a clearer assessment of whether activation in the dual-task condition is truly under-additive relative to the activation found when performing each of the component tasks in isolation. We note however, that our previous studies in which participants combined the sentence task used here with a mental rotation task (Just et al., 2001; Newman et al., 2007) did include such a single-task sentence listening condition, and found that activation in the dual-task condition was under-additive in both language and spatial processing areas relative to the activation that would be predicted on the basis of that found in each of the two single-task conditions.

The new findings raise the obvious point that if listening to sentences degrades driving performance, then probably a number of other common driver activities also cause such degradation, including activities such as tuning or listening

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to a radio, eating and drinking, monitoring children or pets, or even conversing with a passenger. However, it is incorrect to conclude that using a cell phone while driving is no worse than engaging in one of these other activities. First, it is not known exactly how much each of these distractions affects driving, and it may indeed be interesting and important to compare the various effects, and try to find ways to decrease their negative impacts. Second, talking on a cell phone has a special social demand, such that not attending to the cell conversation can be interpreted as rude, insulting behavior. By contrast, a passenger who is a conversation partner is more likely to be aware of the competing demands for a driver's attention and thus sympathetic to inattention to the conversation, and indeed there is recent experimental evidence suggesting that passengers and drivers suppress conversation in response to driving demands (Crundall et al., 2005). Third, the processing of spoken language has a special status by virtue of its automaticity, such that one cannot willfully stop one's processing of a spoken utterance (Newman et al., 2007), whereas one can willfully stop tuning a radio. These various considerations suggest that engaging in conversation while concurrently driving can be a risky choice, not just for commonsense reasons, but because of the compromised performance imposed by cognitive and neural constraints.

4. Experimental procedures

4.1. *Participants*

Twenty-nine right-handed native English speakers (14 females), ages 18–25, were included in the analysis. Functional imaging data from five other participants were discarded due to excessive head motion or other technical problems. All participants were licensed drivers and all reported at least some previous experience with video driving games. Each participant signed an informed consent that had been approved by the University of Pittsburgh and Carnegie Mellon University Institutional Review Boards. Prior to testing in the scanner, each participant completed at least two 5-min practice runs involving the driving alone and the driving with listening conditions. Participants who made more than 40 road-maintenance errors (see below) in either of these runs received an additional 5-min practice run. If they did not complete the 3rd practice run with less than 40 road-maintenance errors, they were excluded from the study. In addition, participants who experienced motion sickness during the practice were not included in the fMRI study.

4.2. *Experimental paradigm*

The experiment consisted of two experimental conditions, each containing three 1-min blocks of driving, along with a baseline fixation condition. In the "driving-alone" condition, participants steered the vehicle through the driving simulation without presentation of auditory stimuli. In the "driving with listening" condition, participants steered the vehicle through the driving simulation while simultaneously listening to the general knowledge sentences and verifying them as true or false. Each sentence was presented for 6 s, with a 5-s delay between sentences within the block. A short tone sounded at the end of each sentence to signal the participant to respond, and failure to respond prior to the onset of the next sentence was treated as an error. Five sentences were presented within each block of driving in this dual-task condition. A 24-s block of fixation was presented before and after each block of driving. In this fixation condition, participants fixated on a centred asterisk without performing any task. This fixation condition provided a baseline measure of brain activation with which to compare each experimental condition.

The order of the two experimental conditions was alternated across participants, and two versions of the experiment were created to counter-balance condition order and the particular roads assigned to each condition. Fourteen participants completed one version and fifteen completed the other. Each version contained the same roads in each condition, but with the opposite direction of travel across the two conditions. This counter-balancing was intended to minimize practice effects influencing the quality of driving for each condition. Initial analyses found no reliable differences between the two orders of conditions in either of the behavioral measures of driving accuracy, in sentence comprehension performance, nor in any of the voxel-wise contrasts between conditions conducted on the fMRI data. All analyses reported here were performed after collapsing across the two versions.

Participants were instructed to attempt to maintain the position of the vehicle in the center of the road and to avoid hitting the sides of the road. They were told that in the driving-alone condition they should focus their full attention on the driving task, and in the driving with listening condition, they should attend equally to both tasks. For the sentence task, they were instructed to wait until the tone at the end of the statement, and to respond as quickly as possible without sacrificing accuracy.

4.3. *Stimuli and apparatus*

The driving simulation was created using WorldToolKit simulation development software (Sense8 Software, Engineering Animation, Inc., Mill Valley, CA) and was integrated with experimental control software specifically written to provide for synchronization with the MRI scanner, presentation of auditory items, and the recording of button press responses and driving performance. The simulation was run on a PC with a NVIDIA Riva TNT2 64 Pro graphics card. The driving simulation was rear projected by an LCD projector onto a semi-translucent plastic screen inserted into the bore of the scanner behind the participant, allowing participants to view the screen through a pair of mirrors attached to the head coil of the scanner. The visual angle of the display subtended approximately 30° in the horizontal dimension. The simulation provided the participant with a view of rural winding roads, occasionally encountering hills and passing by bodies of water (see Fig. 1 for an example). The simulation involved daytime driving with good visibility and road conditions. There were no intersections, hazards, or other vehicles on the road. The apparent speed of the vehicle was fixed at 43 mph (69.2 km/h). The participants' only control over the simulation was the steering of the vehicle to the left or right by use of an MRI-compatible computer mouse (6 participants) or computer trackball (23 participants) with their right

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hand[2]. A red dot at the bottom of the display indicated steering movements to provide feedback on the position of the virtual steering wheel. No other instruments of the vehicle were displayed. If the participant happened to steer the car into the side edge (berm) of the road, the program prevented the vehicle from leaving the road but recorded each time it made contact with the boundaries of the road as a road-maintenance error. The x, y, and z, coordinates (in virtual "feet") of the position of the vehicle within the virtual environment was sampled at the frame rate of presentation (approximately 10 frames per second, providing a measure of how well the participant tracked an ideal path along the road. Although this simulated driving task obviously differs in significant ways from real driving, Horey and Wickens (2006) found that studies that used simulated driving and those that were conducted in the field with an instrumented automobile produced similar combined effect sizes of distraction on driving performance, suggesting that simulated driving generalizes reasonably well to real-world situations.

The sentences were presented using a high-fidelity MRI-compatible electrostatic headset (Resonance Technology, Inc., Los Angeles, CA) that attenuated scanner noise and allowed the auditory stimuli to be intelligible at a comfortable listening level (approximately 60 dBA). Participants responded regarding whether each sentence was true or false using two optical buttons in their left hand. The left button in the participant's left hand was always used for "false", and the right button was for "true". The sentences were factual statements requiring retrieval of general semantic information expected to be common knowledge among our sample of university students. An example of a true statement is "Botany is a biological science and it deals with the life, structure, and growth of plants." An example of a false statement is "A phobia refers to a person's extreme attraction to some object, situation, or person".

4.4. *Behavioral measures*

Reaction times and errors were recorded for the sentence comprehension task to ensure that participants were performing the task. Two measures of driving accuracy were derived from the record of the participant's path along the virtual road. The first, which we refer to as road-maintenance errors, was the number of times the participant made contact with the boundaries (berms) of the road. The second was the root mean square deviation from an ideal path down the center of the road. Differences between conditions in these measures were assessed with paired t-tests.

4.5. *fMRI parameters*

The imaging was carried out at the University of Pittsburgh Magnetic Resonance Research Center on a 3-Tesla GE Signa scanner using a GE quadrature birdcage head coil. For the functional imaging a T2*-weighted single-shot spiral pulse sequence was used with TR = 1000 ms, TE = 18 ms, and a flip angle of 70°. Sixteen adjacent oblique-axial slices were acquired in an interleaved sequence, with 5-mm slice thickness, 1-mm slice gap, and a 20 × 20 cm FOV. The spiral k-space data was regridded to a 64 × 64 matrix, resulting in in-plane resolution of 3.125 × 3.125 mm.

4.6. *fMRI data analysis*

The image processing was carried out using FIASCO (Eddy et al., 1996) and SPM99 (Wellcome College Department of Cognitive Neurology, London, UK) software. Pre-processing steps carried out in FIASCO included reconstruction of the k-space data and correction for spikes, linear signal drift, and in-plane head motion. The mean estimated displacement across the x, y, and z dimensions after in-plane motion correction of the 29 participants included in the analysis was less than 0.1 mm, and the maximum estimated displacement in any dimension across participants was 2.2 mm. Each participant's functional data were then corrected for slice acquisition timing, realigned, normalized to the Montreal Neurological Institute EPI template, and spatially smoothed (Gaussian kernel, full-width at half maximum = 8 mm), using standard SPM99 procedures. Activation was assessed on a voxel-by-voxel basis within each participant by modelling the time-course of the signal with a general linear model including regressors for the fixation baseline, the driving-alone condition, and the dual-task condition, each convolved with the canonical SPM99 hemodynamic response function. Because the addition of the secondary language comprehension task might be expected to systematically increase the global signal, no global scaling was applied to the data to avoid biasing the estimates of activation in this condition.

Group activation was assessed with a random-effects model in which differences in the beta-weights from the first-level analysis of each participant were assessed with one-sample t-tests. For these voxel-wise analyses of differences between conditions a threshold of $p < .0001$ was adopted at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level (an extent threshold of 81 voxels). To compare the amount of activation in a given anatomical area across experimental conditions, 32 anatomically-defined ROIs that covered the activation observed in this task were used. The 32 ROI definitions shown in Table 3 were derived from the parcellation scheme developed by Tzourio-Mazoyer et al. (2002). Changes in mean signal intensity relative to the fixation baseline were computed from the averaged time-course data extracted from each of these regions, and these changes were assessed with mixed-effects analyses of variance. No thresholding of the individual participants' activation maps was applied in this secondary analysis, so that the mean percentage change in signal intensity represents the amount of activation in the area in each condition, after adjusting for the size of the anatomical region of interest.

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[2] A technical problem with the MRI-compatible mouse developed after the sixth participant was scanned, and a more reliable trackball device was used for the remaining participants. Between-subject tests of the effect of input device revealed no reliable differences on either of the behavioral measures of driving, nor on any of the voxel-wise contrasts among conditions conducted on the imaging data.

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