Mind-on-the-Drive: Real-Time Functional Neuroimaging of Cognitive Brain Mechanisms Underlying Driver Performance and Distraction

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ABSTRACT

How do in-vehicle telematics devices influence mind-on-the-drive? We determined the spatio-temporal properties of the brain mechanisms during a simple visual event detection and motor response in a validated driving-like protocol. We used the safe and non-invasive brain imaging methods of functional magnetic resonance imaging (fMRI) and Magnetoencephalography (MEG) to locate the essential brain activated structures and their corresponding temporal dynamics. This study sets the foundation for determining the fundamental brain mechanisms by which secondary tasks (such as cell phone use) may affect the responses to visual events in a laboratory setting. Improved knowledge of the brain mechanisms underlying selective attention in such driving-like situations may give rise to methods for improving mind-on-the-drive.

INTRODUCTION

An essential issue for human factors research is to examine and evaluate the design of human-machine interfaces for the safe and efficient operation of complex equipment under multitasking conditions [1], [2]. In driving, multitasking is required for primary tasks that have to be performed (steering, braking, navigation), as well as secondary tasks that are elective (e.g. cell phone use). Little is known about the brain mechanisms underlying primary driving tasks, much less during secondary tasks. The scientific goal of this study was to set a foundation for determining the neural basis of mental attention shifts that may underlie some driver errors, which includes driver distraction.

Behavioral metrics have been established for measuring on-road driver performance while doing secondary tasks in a vehicle (Angell, Young, Hankey and Dingus [3]; CAMP [4]). These metrics typically involve direct measurements of vehicle behavior (e.g. lane and speed deviations, braking time, headway to preceding vehicle, etc.). Indirect measures such as eyes-off-road time and subjective workload have also been made in these same studies. Laboratory methods for collecting data that is predictive of on-road driver performance have been developed and validated in these same studies. It is relatively straightforward to use analysis of video recordings to determine how long the eyes are on or off the road during secondary tasks. However, it is not as simple to determine whether a driver’s mind is on the drive using such purely behavioral measures.

Some event-detection methods have shown initial promise in measuring mind-on-the-drive. Martens and van Winsum [5] and Olsson and Burns [6] used a peripheral light mounted on a headset to which a driver responds with a hand switch whenever the light turns on. Angell et al. [3] extended these methods by using a central as well as peripheral light mounted on the hood and left outside mirror of the vehicle, respectively. The reaction times and miss rates to the events are measured by the press of a foot switch whenever a light is seen. This technology has shown some initial promise for measuring mind-on-the-drive in some on-road driving experiments [9]. There has also been some limited progress in the difficult task of predicting on-road event-detection variables from even validated static laboratory methods [3], much less non-validated static methods. However, purely behavioral methods for evaluating event detection have inherent limitations.
Drivers might not respond to an event for three separate reasons. First, the driver may make an eye movement to a location sufficiently far from the event such that light from the event does not enter the driver's eyes (eyes-off-road). Second, the light from the event or visual stimulus may enter the eyes, but the contrast or movement may not exceed the sensory threshold such that neural messages are sent from the eyes to the brain. Third, the light might enter the driver's eyes and neural messages be sent from the eyes to the brain, but the brain might not perceive the event (cognitive blindness). The third reason is also termed looked-but-did-not-see, inattention blindness or change blindness. This effect can occur whether an eye movement does or does not precede or follow the missed event. Every combination of these effects is logically possible: eyes and mind might both be off the road, both be on the road, or one or the other only. Indeed, it is well established from cognitive and neurophysiological studies that visual detection is affected by both top-down cognitive attentional effects and bottom-up sensory effects (Posner and Raichle [7]; Corbetta and Shulman [8]). Indeed, it is well established that the "spotlight of attention" can be independently directed to any part of the visual field, and improve stimulus detection, independently of gaze location. Because of this independence, and also because gaze patterns cannot discriminate between sensory and attentional effects, gaze patterns alone are not a sufficient indicator of mind-off-road. Therefore, the current study was undertaken to establish direct physiological methods for measuring mind-on-the-drive. Our objective is to set the foundation for elucidating the neural mechanisms underlying attentional effects of secondary tasks on driver event detection performance.

The notion that event detection is independently affected by attention and gaze variables is supported by principal component analysis of multivariate on-road driver performance data while doing secondary tasks (Young and Angell [9]). Glance variables such as eyes-off-road time, number of glances and mean glance duration have the same positive loadings as event-detection variables on an overall driver demand dimension, accounting for 61 percent of the total variance in driver performance while doing secondary tasks in the vehicle. That is, more eyes-off-road time is associated with more missed events and longer reaction times. But glance variables are oppositely loaded with event detection variables for the second driver performance dimension (interpreted as low-workload-but-high-inattentiveness, accounting for 17 percent of variance). That is, some secondary tasks even with driver's eyes mostly on the road have relatively higher missed event rates and longer reaction times. This dimension identifies tasks that make drivers more inattentive to outside events than expected, given that their eyes are on the road.

Like glance behavior, self-reports of attention to the road (e.g. subjective situation awareness metrics) may also not be adequate measures of mind-off-road. Subjective metrics assume that drivers are aware of being distracted —yet drivers may be unaware that they are missing things on the road [10], [11]. What driver has not carefully looked to both sides before entering an intersection, only to be startled by an oncoming vehicle that was in the field of view but not seen? What driver has not been alerted by someone else to an unnoticed impending event in their vehicle path? Some drivers may be unaware that they are capable of missing events directly in front of their eyes (that is, they are blind to change blindness [12]). It is unclear how measurements of eye movements can account for cases where someone is looking right at something and does not see or react to it [2]. In a simulator experiment, Greenberg et al. [13] asked participants to pay attention to a driving scene, and to detect and respond to visual events at different locations in their visual field. Participants were also asked to perform secondary tasks such as answering a phone and carrying on a conversation. Their study found missed events for incoming calls that were not explainable by eye movements: "Drivers were actually looking out the windshield and still failed to detect events occurring directly in front of their vehicle." Huettel et al. [14] using a change-blindness visual paradigm during fMRI concluded that "Detection of change, when transient visual cues are not present, requires activation of extrastriate visual regions and frontal regions responsible for eye movements." That is, with no transient visual sensory cues, the brain must engage eye movements in a search strategy to detect a change in a visual scene.

Glance behavior in simulators, although different than on-road glance behavior, can predict on-road glance behavior via linear regression analysis [3]. Unfortunately, on-road event-related behavior is difficult to predict from static event behavior, as shown in the same studies. The reasons why on-road event variables do not bear a simple relationship to static measurements are not yet fully known. The current study takes an event protocol that has extensive behavioral data collected both statically and dynamically (Angell et al. [3]). Any data collected in it can therefore be related to both static and on-road studies. This study is the first we are aware of that uses the same protocol in a brain imaging study as in static and dynamic vehicle testing studies.

The knowledge gained may help understand how the brain performs in dual-task situations in general [15]. In particular, such knowledge may help explain how the performance of secondary tasks such as conversing on a telematics system may affect reaction times or miss rates to events in laboratory simulator studies [13], [16], but not have a determinable effect on real-world crashes severe enough to deploy an air bag (Young [17]). Such knowledge may also allow a more precise determination of which secondary tasks have appreciable effects on real-world driving performance [18], [19], and which do not.
OBJECTIVES AND PARADIGM

The immediate research objective is to determine the underlying location and dynamics of the neural mechanisms that underlie event detection in a driving-like scenario. The applied objective is to determine better methods for assessment-related behavior that can lead to more effective on-road predictions from laboratory data.

The basic paradigm has been previously applied to the study of the effect of secondary tasks on driving in simple static simulators and on-road studies [3]. When extended to include secondary tasks in the brain-imaging environment, this project will help fulfill its long-range scientific objective to help determine the neural basis of mental attention shifts that underlie driver errors during the performance of secondary tasks in the vehicle (i.e., driver distraction).

Two questions are key: (1) What brain systems are activated and when during normal driving? (2) What changes in this baseline brain activity are induced by secondary non-driving tasks? To answer the first question, we used functional Magnetic Resonance Imaging (fMRI) at the Wayne State Medical School Transportation Imaging Laboratory to identify activated brain structures in a simple driving-like paradigm. This paradigm has been validated with on-road and static vehicle driver performance data [3]. We also used Magnetoencephalography (MEG) at Henry Ford Hospital to determine the temporal dynamics of those pathways in the same driving-like paradigm. We report here a preliminary answer to the first question, particularly with regard to a simple light event detection and response reflex. To answer the second question, we intend to add an auditory-verbal secondary task (cell phone conversation) to the event detection and response task in the same driving-like paradigm. We will then assess the spatio-temporal brain changes and compare them to the baseline established in this study.

Both the fMRI and MEG experiments reported here used a behavioral paradigm that has been well validated to predict on-road behavior for many major driving performance metrics [3], despite its simplicity and low cost compared to elaborate driving simulators. It uses digitized videos of real-world driving scenes, recorded during daylight hours in the summer while driving on various roads and highways in southeast Michigan. The scenes were shot from the inside of a vehicle looking outward, as near to the driver’s point of view as practical, using a high-quality video camera [20]. The interior windows of the vehicle were shielded (except for the windshield) to prevent reflections and glare.

Small light events are superimposed at the bottom or to the left of the driving video when shown to the participants, at unpredictable times. The participants are asked to respond when they see a light event by pressing a foot switch in a braking-like manner. We typically use a forward light on the hood of the vehicle, and a peripheral light on the left-side driver’s mirror, in on-road and laboratory studies [3]. We use a left-foot switch similar to an old-style headlamp dimming switch in the road studies, and a standard brake pedal operated by the right foot in the static laboratory. We used similar forward and peripheral lights in the MEG experiments reported here, with a right foot pedal. We used a single forward event light in the fMRI studies, and a button operated by the right hand, rather than a foot pedal.

Previous studies have used a single peripheral light with a hand switch, [5], [6], [21]. These studies, combined with studies [3], [4], conclusively demonstrate that simple light detection tasks when used with appropriate parameters and conditions in a driving context can provide a highly sensitive measure for workload variations induced by traffic, the road environment, driving experience, human-vehicle interface complexity or secondary task difficulty. Although successful at predicting overall workload variations, the predictive ability of static event light detection measures for specifically predicting effects on crash rates in real-world driving (e.g. Young [17]), has yet to be shown.

FMRI EXPERIMENT

Functional Magnetic Resonance Imaging (fMRI) is a technique for localizing brain activity by non-invasively measuring the magnetic fields related to blood flow associated with neural activation [22]. Its strengths are that it measures these responses with millimeter spatial resolution, correlates function and anatomy, and is safe and non-invasive. We used whole-brain fMRI to identify the key brain systems involved in visual event detection and response during a limited form of simulated driving.

In the first published fMRI study of simulated driving, Walter et al. [23], using a computer driving game, found two areas of perceptual-motor activation: sensorimotor cortex and cerebellar regions.

Calhoun et al. [24], using a validated computer-generated driving scenario, used independent component analysis to identify specific spatio-temporal brain components involved in driving: (1) vigilance (spatial attention); (2) error monitoring and inhibition (motivation and risk assessment); (3) high-order visual/motor integration and low-order visual; (4) motor control (fine and gross), and (5) visual monitoring. During the simulated driving scenario, brain regions associated with vigilance and spatial attention (e.g. fronto-parietal cortex) decreased their involvement during driving, and those associated with error monitoring and inhibition (e.g. anterior cingulate cortex) showed an exponential decrease during driving. The other components increased in activation while driving.

A joystick simulation study by Toyota of a car-following task during fMRI [25] found activity in cerebellum (visual feedback during smooth tracking of the preceding car);
basal ganglia, thalamus, premotor cortex (movement selection); and a premotor-parietal network (visuo-motor coordination). Their study also found that “Task performance was negatively correlated with anterior cingulate activity, consistent with the role of this region in error detection and response selection.”

This previous work on more complex forms of simulated driving included more interactive components such as acceleration, deceleration, navigation control or car-following. We were mainly interested in isolating and identifying the brain systems activated during a specific but relatively simple driving behavior, namely visual event detection and response, in the context of immersion in a real-life driving visual scene.

**FMRI METHODS**

Data were acquired with a 1.5 Tesla Siemens Sonata whole-body MRI scanner (Fig. 1) equipped with a head volume coil. Functional imaging methods were used (see [26], [27], [28] for parameters). Data were analyzed offline using Statistical Parametric Mapping software (http://www.fil.ion.ucl.ac.uk/spm/).

**Stimuli**

Real-world driving scenes were shown through magnetically shielded liquid-crystal display goggles (Resonance Technologies, Northridge, CA). The participant’s ears were insulated from intermittent magnet activation noise with headphones (Fig. 2). A microphone allowed communication between the participant and experimenters at all times.

Each screen of the goggles subtended approximately 30 degrees of visual field. The goggles gave a more immersive experience than viewing a projection screen or video monitor, because no visual stimuli other than the driving scene could be seen. No driving sounds accompanied the video.

**Task Conditions**

In the main experiment, the participant’s brains were imaged during three task conditions: (1) EVENT - the event light alone; (2) VIEW - the driving video alone; and (3) DUAL - the driving video and the event light together (see Fig. 3). In the VIEW and DUAL conditions while viewing the real-life driving scene, participants were asked to imagine driving without overt motor responses such as moving the arms or head. (Indeed, they were asked to remain still to the extent possible, to minimize head movement artifacts in the fMRI.) A finger press and eye movements constituted the only overt motor activity during the task conditions.
Figure 3. Screen shots of the driving video and target visual events presented to subjects during the EVENT task (condition 1, top panel), the simulated driving VIEW task (condition 2, middle panel), or the DUAL task (condition 3, bottom panel). Each of these task conditions alternated four times with a blank screen with a crosshair in the center for each participant (see Fig. 4).

It should be noted that the DUAL task condition implemented here is not a dual task condition in the usual sense of a primary driving task and a secondary non-driving task. The DUAL condition here is the analog of two primary driving-like tasks: viewing the roadway and responding to events. It is intended to set the foundation for later experiments (not reported here) of the neural effects of a secondary task (e.g. cell phone usage) on a primary event detection brain response, in the context of a driving-like scenario.

Recording Methods

Each of the three scanning sessions consisted of four, 40-second blocks of one of the conditions described above, with each block alternated with a 40-second baseline period during which participants fixated on a centrally placed crosshair (baseline fixation condition), producing 360 seconds or six minutes of time for each session (Fig. 4) [30].

Participants received seven visual events during each block of the event task in the EVENT and DUAL conditions 1 and 3, representing a total of 28 events over the course of each of those two conditions. All three task conditions were presented to each participant, with the order of the three conditions counterbalanced across participants.

Six normal right-handed volunteers (three male and three female, 22-28 years old) participated in the experiment. All participants had normal or corrected vision. The data were pooled across the six participants for each of the three conditions. The level of activation for each of the three conditions was compared with the activation of the fixation baseline. A separate comparison was made of condition 3 vs. condition 2. The score at each three-dimensional volume element (voxel) for each condition was evaluated for statistical significance using the t-test with threshold at $p < 0.05$, corrected for multiple comparisons.

BLOCK-RELATED FMRI RESULTS

Multiple neural systems were associated with block-averaged analysis of all three conditions, when compared to fixation baseline (for details, see [26], [27], [28]).

1. EVENT Task vs. Baseline (Crosshair Fixation)

The event light and hand response condition alone (Fig. 3, top panel, condition 1) showed clearly identifiable brain responses to the event light in visual cortex and
the motor response in primary motor cortex and supplementary motor area, when compared to the baseline condition (brain image not shown).

This condition was a control to show that the well-known visual and motor brain areas connected with a simple visual-motor reflex such as a hand response to a light event could be detected and measured with the fMRI method. A counterpart in real-world driving would be implausible: sitting in a stationary vehicle pressing a brake pedal in response to a stoplight on a black field of view. For such reasons, this control condition is not run in our on-road or static vehicle driver performance experiments [3].

2. VIEW Task vs. Baseline (Crosshair Fixation)

Viewing the driving video without the event light (VIEW condition 2, Fig. 3, middle panel), vs. baseline activated large brain areas, including visual, parietal and temporal cortex and frontal areas, including BA6 (brain image not shown). In particular, these activations involved statistically significant activation increases in the left precentral gyrus, left superior parietal lobe, left supramarginal gyrus, left inferior frontal gyrus, visual cortex, cerebellum, anterior cingulate gyrus, and basal ganglia. Activation of these brain regions suggested a greater role for motor coordination and control, vigilance, preparatory motor processes, and the regulation of the temporal aspects of specific motor responses.

Indeed, the dynamic brain activation patterns could be viewed in real time on a monitor in the control room using the custom real-time fMRI software TurboFIRE [31], [32], [33], [34]. During pilot experiments a large increase in brain activation of one participant was noted by the experimenters at the same time as the video showed passing an 18-wheel truck (Fig. 3, bottom panel). When questioned after the trial, the participant reported that he had concerns about passing such large trucks in his everyday driving. This observation, although anecdotal, confirmed the objective observations that the driving video actively engaged more than just visual cortex in participants’ brains. In fact, it was consistent with the fMRI activations seen in active driving in a simulator [24].

Viewing the driving video by itself is used both as a task to contrast with the baseline crosshair fixation condition, and again as a control condition to contrast with the DUAL task condition (see below). As proof that VIEW is a driving-like task it is noted that the large brain activations in motor as well as vigilance regions (not just visual regions) indicated that participants were actively immersed in the driving scene as intended; that is, they were making covert mental responses consistent with overt driving behavior even though they did not make body movements such as turning a steering wheel or rotating the head. The VIEW counterpart in real-world driving would be simply driving down the road without having to respond to external events or doing a secondary task. This condition is run in our on-road and laboratory driver performance tests as a practice trial [3].

3. DUAL Task vs. Baseline (Crosshair Fixation)

Viewing the driving scene while responding to the red light (Fig. 3, bottom panel), when compared to baseline, activated similar brain areas as in conditions 1 and 2, but with additional activation in motor cortex.

The detailed increases in activation vs. baseline are shown in Fig. 5 as the yellow and red colored areas. These indicate statistically significant changes in activation (note the high t-scale at bottom of Fig. 5).

Figure 5. Brain response to DUAL task (video + event) vs. brain response to baseline. The left two images show side views of the brain at different “slices” of a vertical plane. The right two images show top views of the brain at different “slices” of a horizontal plane. There is widespread activation from the driving video plus event task compared to baseline. Key: PM (medial pre-motor and also some motor), PC (precuneus), AC (anterior cingulate). SPL (superior parietal lobule), FEF (frontal eye fields and some pre-motor), P (pulvinar), CH (caudate head), Cb (posterior cerebellum). Color scale at bottom is t-score for the comparison of brain activation vs. baseline.

These regions are again part of neural systems involved in low and higher level visual processing (Brodmann’s Area (BA) 17-19, lingual and fusiform gyri, pulvinar), preparatory motor responses (BA 6 and BA 8), motor control/coordination (cerebellum, basal ganglia), as well as attention-related processing (anterior and posterior cingulate cortex, inferior and superior parietal lobules, temporal-occipital junction and the area of the frontal eye fields). Several of these regions are identified with letter codes in Fig. 5. Other noteworthy sites of activation were observed in the inferior temporal gyri and medial temporal sites (parahippocampal gyrus, uncus).
Average driver performance data collected in a vehicle parked in a garage with a television monitor showing the same driving scene as used here, and with similar event lights, is predictive of on-road driving performance [3].

4. DUAL Task vs. VIEW Task

A comparison was made of the brain responses of the DUAL task (condition 3, Fig. 3, bottom panel) to the brain responses to the VIEW task (condition 2, Fig. 3, middle panel). Each of these task conditions was alternated with the baseline crosshair. But the response to the DUAL task could be compared to the VIEW task through mathematical analysis. This comparison reflects the areas of activation specific to the event task, when done in the context of viewing a driving video, vs. the effects of the video alone. This comparison of the brain activations of DUAL vs. VIEW tasks is shown in Fig. 6 as the colored regions, all of which were statistically significant.

In general, the activations were restricted to smaller volumes than in the DUAL task vs. baseline comparison (Fig. 6 has less colored area than Fig. 5). Also, the activations were not as strong: Fig. 6 has a smaller upper range of t-values (7) than Fig. 5 (18). This contrast reveals brain activations specific to event detection during driving-like behavior are identified in Fig. 6, apart from the effects of the video by itself (condition 2), event detection by itself (condition 1), or their combination (condition 3).

In particular, the comparison of the DUAL task vs. VIEW task in Fig. 6 shows there was reduced activation (compared to DUAL task vs. baseline in Fig. 5) of several fronto-parietal regions, as well as cortical and sub-cortical regions of the motor system seen in Fig. 5 (pre-motor cortex, cerebellum, and basal ganglia). Several of the regions with reduced activation compared to DUAL vs. baseline are identifiable in Fig. 6. Other significant decreases in brain activation from controlling for the activation from the video task itself were centered on prefrontal regions in the superior frontal gyrus (region SPL in Fig. 6, left bottom brain image), known to be involved in higher level cognitive functioning. Again, the fact that these areas continue to show activation after contrasting them with the activation from the video alone, suggest they are involved in the event detection task during brain responses activated by the video.

In short, we compared the brain responses to viewing the driving video with event detection, to without event detection. This comparison indicates a frontal-parietal network, including occipital and thalamus regions, is associated with event detection in the context of a driving-like scenario. These areas strongly suggest brain involvement in coordinating visual attention, attentional control, stimulus processing, response selection and motor execution during the event detection task in this scenario; more specifically than in the event task by itself, or the video by itself.

For an analogy to real-world driving, this scenario is the equivalent of comparing (a) driving while responding to a visual event such as a brake or traffic light vs. (b) just driving. On-road data show that responding to event lights plus driving has a somewhat higher workload demand via most driver performance metrics than just driving [3] as would be expected from common sense. The more specific activations seen in Fig. 6, when compared to Fig. 5, suggest specific brain regions that
should be looked at in later work studying the effects of secondary tasks on event detection in the context of driving.

**Behavioral Event Analysis**

There were few misses of any lights in these experiments, consistent with on-road studies of baseline driving with similar protocols for the event lights as used here [3]. The mean success rate for the DUAL task condition 3 was 100 percent (no misses). The mean success rate for the EVENT task condition 1 was 98 percent, not a statistically significantly difference. The mean response time for the DUAL task (condition 3) was 611 milliseconds, while that for the EVENT task alone (condition 1) was slightly faster at 550 milliseconds, indicating a small dual task deficit of 61 milliseconds (DF 5; \( t = -2.68, p < 0.05 \)). (It should be cautioned that this result is for only six participants and may not hold up for larger sample sizes.) The neural mechanisms producing this small time difference cannot be reliably determined from fMRI studies with their slower time scales compared to MEG imaging. However, it is interesting to note that the larger amount of brain activation in the DUAL task condition 3 (Fig. 5) actually was associated with slower reaction times than the more restricted activation from just the event light task by itself (condition 1, not shown).

Again for analogs with on-road driving, this scenario is equivalent to comparing driving plus responding to roadway events (condition 2) vs. responding to events with nothing else visible except the event light (condition 1). We have not explicitly tested this comparison in our static or on-road driving studies [3], because we have had no reason for testing a participant’s response to the lights against a black field of view (which would not be feasible on-road anyway). But it is plausible that a slightly faster response might be expected to a light event in a black vs. complex visual background.

**EVENT-RELATED FMRI RESULTS**

A second analysis method (Hsieh et al. [35]) used event-related analysis methods in the brain software program SPM99. This method analyzed the same fMRI data that was analyzed in conditions 1 and 3 above with event data. Condition 2 had no event data and so could not be analyzed with this method.

Event-related analysis provides a close-up window to look at the brain activity with a fine-grain and more precise perspective than block analysis. The event-related method time locks the participant’s brain responses according to the red light events (see Fig. 4 bottom), rather to the blocks of the different conditions (Fig. 4 top). There is no need to compare each condition to the baseline brain activity with the crosshairs alone, as in the block-analysis method.

Fig. 8 shows the brain responses to the DUAL task (driving video with red light detection task) when analyzed with event-related analysis. This analysis showed similar neural networks as the boxcar analysis presented earlier: large fronto-parietal networks, thalamus, claustrum and cerebellum. This event-related analysis confirms, in the DUAL task, the recruitment of neural systems known to be involved in visuo-motor multimodal processing and integration.

An additional task condition was examined for four of the six subjects. This fourth task condition (not discussed in the block-analysis method described above) consisted of the DUAL condition in one 40-second block, followed by the VIEW condition in the next 40-second block, and so forth for four repetitions. There was no central crosshair baseline block in this task condition. This fourth condition was added to more directly determine the areas of activation specific to the event task in the context of viewing a driving video vs. the effects of the driving video itself. This direct DUAL vs. VIEW task condition was designed to answer the same question as the DUAL vs. VIEW post-hoc analysis in the block analysis method – to examine the event detection task in a driving context, but now more directly controlling for the effects of the video itself.

Fig. 9 shows that using event-related analysis, this condition showed the activation of mechanisms for attentional executive control that included the anterior cingulate gyrus, left motor cortex and the middle/superior frontal areas in the right hemisphere. This fourth task condition used in the event-related analysis also confirms the block analysis in that the DUAL task, when compared with the video viewing by itself, recruits neural systems known to be involved in visuo-motor multimodal processing and integration and increased attention demand.

The consistent findings of the block-related and event-related analysis approaches validate the results reported here using functional MRI methodology for the investigation of high-level, multitasking activities such as simulated driving and event detection.
Figure 7. **L. Precentral Gyrus**: finger press from right hand. **L. SPL (BA 7)** (superior parietal lobe) and **L. supramarginal gyrus**: sensorimotor integration and higher cortical function (such as monitoring and manipulation). **L. IFG (BA 45/47)**: higher cortical function (i.e., executive function), such as decision making, monitoring and selective attention. **Anterior cingulate gyrus**: attention, workload and task demand.

Figure 8. **L. Precentral Gyrus**: finger press from right hand. **L. SPL (BA 7)** (the superior parietal lobe) and **L supramarginal gyrus**: sensorimotor integration and higher cortical function (such as monitoring and manipulation). **L. IFG (BA 45/47)**: higher cortical function (i.e., executive function), such as decision-making, monitoring and selective attention. **Anterior cingulate gyrus**: attention, workload and task demand. **Visual cortex (BA18/19)**: visual sensory function. **Cerebellum**: motor sequencing, temporal coordination.
FMRI DISCUSSION

The goal of these fMRI experiments was to identify the spatial neural correlates of a common driving behavior, namely visual event detection, performed as part of a limited simulated driving protocol. The results are in accord with what is well known about the spatial aspects of brain function, e.g., motor cortex activity with manual activity, visual cortex activity increase with complex imagery, Brain areas associated with higher brain functions were also identified, as elicited by the driving video.

In particular, we found evidence for the involvement of multiple brain regions while participants detected and responded to target visual events that appeared in real-world driving scenes used to simulate driving. These brain areas make up widespread and interconnected cortical as well as cortico-sub-cortical anatomical brain networks. In particular, the frontal and parietal cortical regions identified are known components of several large-scale brain systems important during neural processes that include not only visual attention, but also attention control, stimulus processing, motor selection and responses. The interaction of the frontal and parietal systems is thought to control how, what and where we pay attention in our visual environment. These interrelated neural activities are necessary during key driving tasks and behaviors in general, and visual event detection and response in particular. We interpret these findings as reflecting interrelated neural processes associated with visual attention, attention control and allocation, stimulus processing, response selection, execution and timing, all of which are critical during driving. The use of functional neuroimaging techniques such as fMRI is an important technique in the investigation of complex multitasking behaviors such as simulated driving.

The spatial networks identified with fMRI are a required foundation for MEG experiments that can then determine the temporal dynamics of those networks. In particular, fMRI determined the spatial locations of the brain mechanisms involved in the visuo-motor reflex arc giving rise to the foot response to an event light in this paradigm. The timing relationships of those brain mechanisms can then be revealed through MEG experiments, because of the higher temporal resolution capabilities of MEG. The combination of fMRI and MEG experiments in understanding the spatio-temporal properties of the basic reflex arc is required for the eventual study of the neural basis of how secondary activity (such as in auditory-vocal pathways) might influence the timing of primary visual event detection and response reflex pathways. It is logically necessary to understand the neural dynamics of normal behavior, before possible changes to that behavior from secondary activity can be understood. This approach can also be extended to study other neural mechanisms underlying impaired driving, as potentially influenced by factors such as aging, alcohol, brain injury, drugs, fatigue and inexperience.
MEG EXPERIMENT

Magnetoencephalography (MEG) is a technique for localizing sources of electrical activity within the human brain by non-invasively measuring the magnetic fields arising from such activity. Its strengths are similar to fMRI in that it correlates function and anatomy, and is safe and non-invasive with no risk to participants. However, it improves on fMRI in achieving millisecond temporal resolution at the expense of lower spatial resolution.

The variability of MEG data is low. Studies of within-subject variability of temporal, spatial, and strength of neuronal activation have been conducted using repeated runs [36], [40]. Bolander et al. [37] found the variability of source location induced by the rescaling to a common MRI brain was approximately five millimeters. In short, while amplitudes of activity can vary significantly, the timing and location of imaged brain activation is stable from run to run and across individuals.

In this study MEG scans were performed using the same limited automobile driving simulation paradigm as the fMRI experiments. The main objective was to determine if MEG imaging can identify the dynamics of the cortical regions involved in primary driving-like tasks during this simple driving simulation paradigm. The secondary objective was to combine MEG and fMRI data to create a high-resolution space-time “movie” of neural activity in the conscious human brain during simulated driving and event detection, to serve as a foundation for the future investigation of the effect of secondary tasks.

MEG METHODS

A 148-channel whole-head Neuromagnetometer (Magnes WH2500 4-D Neuroimaging) was used to measure magnetic fields from the heads of four females and one male between 30 and 55 years of age, all of whom possessed a current driver’s license. Measurements were taken inside a magnetically shielded room located in the Neuromagnetism Laboratory at Henry Ford Hospital. The participant lay comfortably on a bed inside the room. The Neuromagnetometer helmet containing the detector array was placed around the participant’s head in close proximity to the skull surface (Fig. 10).

Stimulus-Response

A mirror angled at 45 degrees was placed in front of the participants’ eyes so they could view the real-world driving scene on the screen (the same video as in the fMRI experiment). The driving scene was projected into the shielded room and onto a large viewing screen via a system of mirrors. Two red light-emitting diodes (LEDs) were affixed to the viewing screen, one in the lower central region, and the second one on the left side of the screen. Fig. 11 shows a mirror image of the participant’s view.

LEDs were randomly activated. Participants pushed a mocked-up brake pedal with their right foot to turn the light off.

While in a supine position each participant attended to surrounding vehicle activity, traffic signals, signs and city scenery in a driving video projected directly in front of him/her. At random intervals either the central or peripheral red light stimulus was turned on and the participant was required to detect the light and push the foot pedal. Subsequent pedal activation turned the light off and produced an audible click sound. For the duration of time between turning the light on, to pedal push, a trigger high code was recorded simultaneously with the MEG data. A different trigger code was used for central and peripheral lights. There were 40 red light stimuli during each study. The test was repeated three times to obtain a total of 120 pedal activation events.
The participant was asked to press the foot pedal as soon as a light was detected. The reaction time between turning the light on and pedal push is shown in Fig. 12 for 40 events from participant #1. On average the pedal is pushed between 0.5-1 second.

The video, lights and foot pedal responses were similar to the methods in laboratory studies validated as predictive of on-road driving behavior [3]. The participant was asked to avoid excessive eye blinks and body movements during data collection. Each participant was monitored by video camera and two-way audio during the time he/she was in the shielded room.

**Data Analysis**

All MEG brain data were band-pass filtered 0.1 to 100 Hertz (Hz), then digitally sampled at 508 Hz. Data collection runs lasted four minutes and included brain responses to 40 brake pedal pushes in response to the red lights. Each participant performed three runs. The timing of the lights and pedal pushes were recorded as coded events on a trigger event data channel that was simultaneously recorded with the MEG data (Fig. 12). In post processing, windows of MEG data extending from –500 to +500 milliseconds of each pedal push were extracted, forward and backward filtered 1-50 Hz and averaged to obtain a single epoch of data.

All 120 pedal push events from the three runs were averaged for each subject to enhance the signal-to-noise of the MEG data used for imaging the sequence of brain electric activation.

Fig. 13 displays participant #1’s averaged MEG data for each of the 148 spatial brain channels. Each line is the brain activation averaged across the 40 pedal push events for a given spatial channel.

MEG localizations were performed using the MR-FOCUSS imaging technique (Moran et al. [38]; Moran [39]; Bowyer et al. [40], [41]). Brain imaging results of the five participants were combined into a single brain activation sequence by rescaling the x,y,z coordinates of imaged activity of each participant to match a common MRI head model.

**MEG RESULTS**

Spectral frequency analysis of the MEG data of the five participants demonstrated the data consisted of two major spectral components. The sequence of brain activation was primarily composed of activity in the 1 to 20 Hz band. The other major component was a 28 Hz frequency that was imaged primarily in the right motor and premotor cortex. In some participants this second component was quite prominent.

For all five participants, bilateral orbital-frontal gyrus activation was greatest at light onset and pedal activation. Significant activation of the anterior cingulate gyrus was imaged between 450 to 400 milliseconds prior to the pedal push as well as 100 to 200 milliseconds after. Significant activation of motor and premotor cortex was observed between 180 milliseconds and 50 milliseconds prior to pedal push. Visual cortical activity was imaged during the time interval 500 to 200 msec before the pedal push, and 100 milliseconds after the pedal push turned the light off (cortical OFF response).

Fig. 14 displays the overlay of the 148 channels of MEG data for participant #1; arrows point to the MEG responses associated with the imaged brain responses in Figs. 15-17. For this participant, brain activation in the primary visual cortex to the light onset was significant within the range of 600 to 450 milliseconds prior to the pedal push (see “lights on” in Fig. 14). This activity was followed within 10 milliseconds by superior frontal and anterior cingulate gyrus activation. Motor activity at minus 270 milliseconds in the precentral gyrus (see Fig. 15B) corresponds to foot and leg control motor activity required to depress the pedal (0 milliseconds). This action turned the light off, creating a visual evoked cortical response +95 milliseconds later in the occipital
cortex (Fig. 15C). A bilateral response in the auditory cortex (not shown) was observed at +111 milliseconds as a result of a slight click noise from the pedal push.

In summary, the high temporal resolution of MEG imaging allows the time of activation and sequence of activation to be determined for regions involved in this task performance. In particular, transient activation of the occipital (visual) cortex was observed after the light was turned on (ON response) and after the light was turned off (OFF response), as seen for example in single-unit recordings from visual cortex (Young, Lesperance and Meyer [42]; Young and Lesperance [43]). Motor activation was detected during eye movements to the light source and prior to foot movement. Imaged motor activity correlated with known visual motor and leg/foot motor cortex locations. The left pre-frontal region (Fig. 15A) is known to be involved in higher-order condition decision-making, such as that required in the decision to make a foot response. Frontal and parietal networks (Fig. 15A,B) were significantly active at multiple latencies throughout this task performance. The orbital frontal gyrus was likely active throughout the run while attending to the driving scene.

MEG DISCUSSION

These MEG findings suggest driving-like tasks recruit neural systems known to be involved in visual-motor multimodal processing and integration, and reveal the dynamics of those neural systems. Similar to fMRI findings (Fig. 5), activity is first seen in anterior cingulate, followed by prefrontal activity, then activity in the cortical motor areas, giving rise to the foot press. Following the foot press, activation was seen in the visual cortex corresponding to the event light turning off.
GENERAL DISCUSSION

Visual event detection and response performed as part of a limited simulated driving setup engages multiple interconnected cortical and sub-cortical neural systems working in dynamic patterns, as observed with the brain imaging techniques used here. The spatial and temporal properties of brain mechanisms underlying a simple driving-related stimulus-response mechanism were identified using fMRI and MEG. The use of brain imaging in investigating the dynamics of neural processing regions activated during simulated driving and event detection and response is quite promising. This work lays the basic foundation needed to understand the neural basis of effects on event detection and response of secondary tasks, aging, alcohol, brain injury, drugs, fatigue, and inexperience. In particular, imaging studies of cell phone conversation tasks using the foundation laid here may reveal the dynamic cortical networks underlying the effects of such tasks on driver event detection as reported in some simulator studies [13]. It is important to understand what underlies such effects as seen in laboratories, even though the available real-world data indicates that telematic conversations are not a causative factor in crashes serious enough to cause air bag deployments (Young [17]).

ON-ROAD VALIDATION

The fMRI and MEG studies reported here were careful to use behavioral protocols that have been previously validated as predictive of on-road driving (Angell et al. [3]). Laboratory experiments using methods that have not been validated may make driving predictions that are not necessarily borne out in real-world driving, giving rise to false positive and false negative errors. A false positive error, also called false alarm, exists in a driving context when a laboratory or simulator experiment predicts, incorrectly, that it has found a problem in real-world driving, where none exists in reality. A false negative error, also called a miss, exists in a driving context when a laboratory or simulator experiment predicts, incorrectly, that a problem was not detected when, in fact, it is a problem in real-world driving.

False Positives?

Several studies have generalized to real-world driving with no published data regarding on-road validation of their protocols or results. In our opinion, this could lead to possible “false alarms” for real-world driving.

One fMRI study using a dual-task condition of mental rotation and auditory sentence comprehension concluded that “a complex conversation may put an end to careful driving” even in experienced drivers (Just et al. [45], their p. 425). However, no data on conversations or driving were tested or examined in the study. Moreover, the authors state regarding their own data: “The behavioral measures indicated that the dual tasks were performed without compromising accuracy in either task” and “…both tasks were being performed with a high degree of conscientiousness” (Just et al. [45], their p. 420).

Other behavioral laboratory studies have used joysticks [46], [47] or simulators [16], [48] with no published on-road validation. Study [16] concludes that drivers engaged in cell-phone conversations “…may actually exhibit greater impairments (i.e., more accidents and less responsive driving behavior) than legally intoxicated drivers.” Study [48] states on the basis of results [49] “that cell phone conversations result in impoverished encoding of information necessary for the safe operation of a motor vehicle.” However, there a number of questions which arise in the context of this study’s findings [50].

In short, in our opinion, non-validated laboratory methods may produce false alarms for real-world driving. A real-world study of millions of customer calls to an advisor was the first analysis of a real-world database that had extensive and actual information about whether a crash serious enough to deploy an air bag occurred at the same time a conversation via telematics was occurring [17]. This study found only two crashes out of 8.1 million calls that occurred while a driver was speaking with a service advisor. It was determined later that there were other underlying causes behind both crashes. Little effect of conversation per se on actual driving performance was also seen by Schreiner et al. [51] in an on-road study of voice-activated dialing with a voice-recognition system. Drivers maintained their speed, remained in their lane and scanned their driving environment (checked mirrors, etc.) similarly to how they would during normal driving.

False Negative?

A simulator experiment with college students found that “when participants were legally intoxicated, neither accident rates, nor reaction time to vehicles braking in front of the participant, nor recovery of lost speed following braking differed significantly from baseline” (Strayer et al. [16], their p. 29). In our opinion, this result is inconsistent with numerous simulator, closed-road, and fMRI studies ([52], [53], [54], [55], [56], [57], [58], [59], [60]). It is also inconsistent with real-world data: in 2003, about 275,000 injuries and 17,013 fatalities or 40 percent of all fatalities in motor vehicle traffic crashes were estimated to be alcohol-related [61].

MEDICAL BENEFITS

The medical consequences of severe motor vehicle crashes are well known. However, the medical importance of motor vehicle crashes is not always explicit in rankings of the major causes of death. Anderson and Smith [62] state, “Motor vehicle accidents are not rankable causes of death...though they can be identified using the standard mortality tabulation lists. Were they included in the rankings...motor vehicle
accidents would rank eighth.” The National Highway Traffic Safety Administration (NHTSA) estimates that driver inattention may be responsible for 25 percent to 30 percent of all police-reported traffic crashes, or about 1.2 million crashes per year in the U.S. [63], [64]. NHTSA is currently focusing mainly on the areas of seat belt use and impaired driving (Runge [65]), but also has some naturalistic studies of crashes in progress (Neale et al. [66]). There is some resource support from NIH and NHTSA for compromised driving studies [67], [68]. It is well known, however, that most crashes happen in broad daylight on open roads with little traffic, with no discernible cause other than generic driver error. While it is commonly understood that drivers at all times have responsibility for safe operation of their vehicle, it would be useful if state and federal governments increased funding priorities to understanding the fundamental neural mechanisms involved in driver attention. It might prove feasible to enhance mind-on-the-drive for all drivers (normal and impaired) if there were a scientific understanding of what mind-on-the-drive actually was.

AUTOMOTIVE BENEFITS

A scientific understanding of the neural basis of mind-on-the-drive has the potential to improve on-road predictions of those task and stimulus features that might lead to mind-off-the-drive in on-road driving. Such work may enhance guidelines for designers of in-vehicle telematics systems as to what should or should not be done in secondary in-vehicle devices so that drivers may maintain high awareness of the road situation. The field of human-vehicle interaction commonly focuses on improving usability of primary driver interfaces, knowledge that does not necessarily transfer to improving usability of navigation and telematics devices that must be attended to only as a secondary priority. In short, a better understanding of the fundamental neural dynamics underlying cognitive attentional factors in driving should lead to a more rapid creation of an in-vehicle environment that maximizes situation awareness of the roadway, while enhancing usability of in-vehicle devices and customer satisfaction.

This analysis of the underlying neural processes may guide the development of integrative cognitive models through which we can better comprehend and investigate driving as a complex human activity (Groeger [69]). The brain imaging techniques when used in conjunction with simple yet validated driving-like protocols offer those engaged in the investigation of driving behavior and performance a complementary tool to existing methodologies involving purely behavioral on-road and laboratory experimental paradigms. This new approach of direct brain measurement opens up a major new field of transportation research, as well as extending current investigations of the neural basis of attentional mechanisms underlying multitasking behavior. Such fundamental knowledge may aid automotive manufacturers in designing safer and more efficient driver interfaces, as well as help educate the general public on their personal responsibilities to keep mind-on-the-drive.

CONCLUSIONS

1. The major brain pathways involved in a simple visual-motor reflex in a driving-like paradigm have been identified using fMRI imaging techniques.
2. The dynamics of those brain pathways have been identified using MEG imaging techniques.
3. The driving-like paradigm used here has been validated for predicting on-road driver performance variables, although static predictions for dynamic event-related variables still need further development compared to other driver performance measures.
4. This study sets a foundation for determining how secondary tasks such as telematics conversations may influence the dynamics of visual-motor reflex pathways, at least in a laboratory setting.
5. This study may lead to potential medical benefits for patients with driving impairments due to attention-deficit hyperactivity disorder (ADHD) or traumatic brain injury.
6. This work may lead to guidelines for the automotive industry and the general public on how to improve driver performance.

ACKNOWLEDGMENTS

We thank Leslie Ash, Yow-Ren Chiang, Dan Fitzgerald, Kunxiu Gao, Roger Hersberger, Zhaid Latif and Shauna Macmillan of Wayne State Medical School for technical support on this project. We thank Stefan Posse for technical and administrative guidance and support during the initial phases of this project, and comments on the manuscript. We thank Sandi Nagel for the references to ADHD and driving. We thank GM Photographic Design for videotaping and digitizing the driving scenes. We thank James Young for assistance in word processing, Linda Angell for continuing support and encouragement, and Vince Calhoun for comments on the manuscript. The research at Wayne State Medical School was supported by an unrestricted gift from the GM Foundation. The research at Henry Ford Hospital was supported by NIH/NINDS Grant RO1-NS30914.
REFERENCES


[20] For functional imaging, a complete cockpit and driver interface simulation, with real-time effects on the driving scene through steering or braking, is not necessarily required. For normal adults, the brain responses for any learned complex behavior can be elicited through the introduction of a critical mass of sensory cues. Also, foot or hand responses to lights, for example, exercise neural correlates of visual event detection and subsequent...
motor activation, both integral parts of driving behavior. That is, the same activation patterns elicited in the simple task are components of similar tasks in more complex assignments.


[22] Strictly speaking, fMRI does not localize neuronal activation by measuring magnetic fields arising from blood flow, but rather through a complicated chain of mechanisms: fMRI signals reflect changes in signal dephasing due to changes in blood susceptibility that are secondary to changes in blood flow and oxygen extraction during neuronal activation.


[29] In the on-road paradigm in Ref. 3 and the MEG paradigm reported here, the light terminated after the driver depressed the brake pedal, not after 2 seconds as in the fMRI method reported here. (The fMRI method required a fixed light offset time because of early technical limitations.) Our later on-road and fMRI paradigms are consistent with the MEG paradigm, which terminates the light with a brake pedal push or after 3.5 seconds if the driver does not respond. However, reaction time is measured from the light onset, not the light offset.

[30] This design is known as a “boxcar” analysis, because average brain responses are taken across the stimulus blocks, and compared to the brain responses during the control blocks. The boxcar analysis contrasts with an event-based analysis, in which averages are taken across events, as reported later in this paper for fMRI and MEG.


[36] Temporal differences are less than 10 milliseconds from run to run during language processing. Strength of neuronal activation tended to be weaker in a second run, compared to the first, by about 30 percent. Between-subject variability of primary cortical responses was less than eight milliseconds in a control group of 18 subjects. Amplitudes of primary visual cortex responses were 17 nanoAmperes as quantified by an Equivalent Current Dipole model of activation.
It was not the intention here to report on-road driving-like behaviors. It is thus similar only to the "baseline" driving conditions in Reference [3]. The current study is intended to lay the foundation for brain imaging experiments that study the effect of nonoverlapping cortical systems in dual cognitive tasks. The current study reports only "primary" driving tasks – watching a road scene, and responding to events. It is thus similar only to the "baseline" driving conditions in Reference [3]. The current study is intended to lay the foundation for brain imaging experiments that study the effect of secondary tasks on the brain responses for primary driving-like behaviors.

Ref. [47] did not report the numbers of simulated objects correctly recognized in the single or dual task simulated driving condition for either case in [48]. But the difference in the number of simulated objects recognized in the two conditions can be estimated from the numbers in [48], even without knowing the method used for correcting for guessing. In the first case in [48], the difference in probabilities 0.21 and 0.16 for the two conditions is 0.05. Because there were 15 objects in each condition, it can be estimated that about 0.75 fewer objects (0.05 times 15) were recognized in the dual task than single task condition in this first case. In the second case in [48], only 61 percent of the total objects met the fixation criterion. Of the 15 objects in each simulated driving condition, it can be estimated that about 0.75 fewer objects met this criterion. The probabilities after correcting for guessing were reported as 0.25 and 0.15 for the single and dual task conditions in this second case of fixated objects only.


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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CAMP: Crash-Avoidance Metrics Partnership

fMRI: functional Magnetic Resonance Imaging

LED: Light-Emitting Diode

MRI: Magnetic Resonance Imaging

MEG: Magnetoencephalography

NIH: National Institutes of Health

NHTSA: National Highway Traffic Safety Administration