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DRIVING AND THE BRAIN: AN IMAGING STUDY

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ABSTRACT

Driving is a complex behavior that recruits multiple cognitive elements. To attempt to delineate the underlying neuroanatomy of this cognitive complexity, we used functional magnetic resonance imaging (fMRI) during driving simulation. We report an imaging study of simulated driving and identify several groups of regions, each modulated differently by our imaging paradigm. In order to parse out the neural networks subserving driving behavior, fMRI analysis must account for simultaneous, interrelated cognitive processes. We decomposed the activation into interpretable pieces using a novel, generally applicable approach, based upon independent component analysis. Signal in the anterior cingulate cortex, an area often associated with error monitoring and inhibition, decreased at an exponential rate during driving, whereas activations in frontoparietal regions, implicated in vigilance, decrease immediately and remain low during driving. Other activated regions, including cerebellum and occipital areas, presumably related to complex visuomotor integration, were also associated with simulated driving.

INTRODUCTION

Driving is a complex behavior involving interrelated cognitive elements including selected and divided attention, visuospatial interpretation, visuomotor integration, and decision making. Such a complex behavior is expected to activate brain regions subserving the above processes. For example, some aspects of driving behavior are that it is 1) performance-related, e.g. perception, attention, 2) motivational, e.g. sensation-seeking, aggression, and 3) there are state variables and individual differences, e.g. age, mood, fatigue and intoxication. Obviously, the three levels relate in complex ways in such behaviors as speeding.

Many of the cognitive elements expected to be involved in driving have been studied separately using imaging paradigms designed to probe discrete brain systems (1). Several cognitive models have been proposed for driving (2), especially for visual processing aspects and driver attributes (3,4). However, such models are complicated and hard to translate into imaging studies. Recently, imaging studies have used subtractive methods to study the neural correlates of driving (5) but have not attempted to study the complex temporal dynamics of driving. There is ongoing work to quantify the individual processes which are expected to subserve driving; however there is little work from a top-down approach, i.e. studying what areas are activated by driving and what emergent properties are revealed.

Functional Magnetic Resonance Imaging (fMRI) of the brain is a technique sensitive to localized changes in blood flow and oxygenation due associated with neuronal firing. fMRI is most often used to compare groups of images in one state ("activated") with those in another ("non-activated"), in a paradigm termed block design. Although useful, such block design paradigms fail to exploit much of the information fMRI provides about the temporal nature of the hemodynamics. Researchers are now capitalizing on fMRI's temporal resolution capacities by studying responses to single stimulus events (6). This enables one to design paradigms analogous to those typically used in cognitive testing or EEG, for example. One can acquire images at the rate of 1 per second and capture information about the temporal properties of the hemodynamic response, a function which reaches a maximum at between four and seven seconds after the stimulus onset.

The temporal dynamics of driving are difficult to study with functional magnetic resonance imaging (fMRI) due to the lack of a well-understood brain-activation model (such as in the block design mentioned previously). Imaging studies utilizing cognitive tasks typically employ subtraction between two types of tasks modified in slight increments (1), and provide visualization of brain regions that differ. There is often no attempt to study the temporal dynamics. Event-related designs can be used to study temporal dynamics, but often rely upon rather rigid modeling assumptions (7).

We approach this problem by using for our analysis a method derived from independent component analysis (ICA), a method that has recently been applied to fMRI data with promising results (8-11). ICA was originally developed to solve situations similar to the "cocktail party" problem (12). The ICA algorithm, assuming independence in time (independence of the voices), can separate mixed signals into individual sources (voices). In our application, we assume independence of the hemodynamic source locations from the fMRI data (independence in space) resulting in maps for each of these regions, as well as the time course representing the fMRI

hemodynamics. We recently extended ICA to allow for the analysis of multiple subjects (13,14). We applied this method to our driving activation data, analyzing the data from all subjects in a single ICA estimation. This provides a way to extract behavioral correlates without having an *a priori* hemodynamic model.

Our paradigm consists of three repeating conditions, resembling a standard block design. While these three conditions provide a way to compare behavior, we do not rely upon simple comparison of the images between different conditions, but rather examine the source locations and the modulation of the temporal dynamics. This approach thus provides a useful way of analyzing complex behaviors not possible using traditional (between-epoch) fMRI comparisons.

EXPERIMENTS AND METHODS

Subjects

Subjects (2 female/13 male; mean age 22.5 years) were approved by the Johns Hopkins University Institutional Review Board, and were compensated for their participation. Subjects were instructed to remain within a predetermined speed range and were compensated additionally if they successfully achieved this goal. Subjects were screened with a complete physical and neurological examination, urine toxicologic testing, as well as the SCAN interview (15), to eliminate participants with Axis I psychiatric disorders.

Experimental Design

We obtained fMRI scans of subjects as they performed a ten-minute task consisting of 1-minute epochs of (A) an asterisk fixation task, (D) active simulated driving, and (W) watching a simulated driving scene (while randomly moving fingers over the controller). Two runs of the task were performed, one having order A-D-W-A-D-W-A-D-W-A, and the other A-W-D-A-W-D-A-W-D-A. Across subjects the order of these two runs was randomized. During the driving epoch, participants were performing simulated driving using a modified game pad controller with buttons for left, right, acceleration and braking. The controller was held using both hands and the thumb of the right hand controlled the left and right buttons while the thumb of the left hand controlled the buttons for acceleration and braking. The paradigm is illustrated in Figure 1. The controller was shielded in copper foil and connected to a computer outside the scanner room though a waveguide in the wall. All ferromagnetic screws were removed and replaced by plastic components.

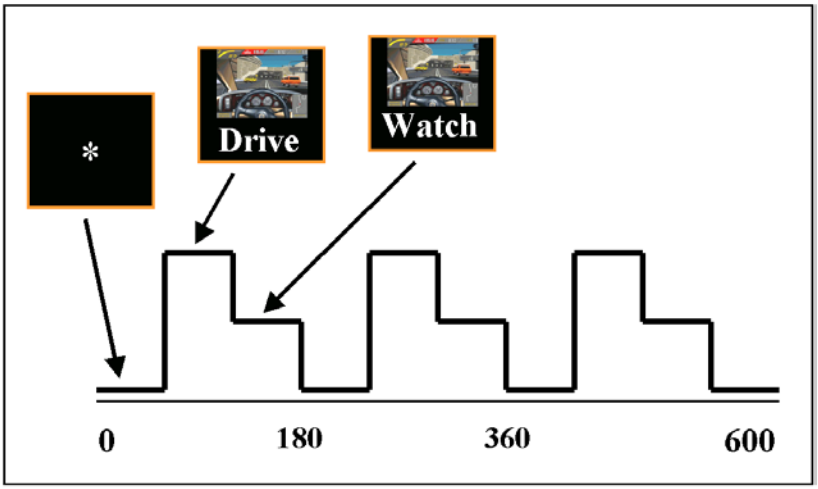

Figure 1: fMRI simulated driving paradigm. The paradigm consisted of ten, one-minute epochs of (A) a fixation target, (D) driving the simulator, and (W) watching a simulation while randomly moving fingers over the controller. The paradigm was presented twice changing the order of the (D) and (W) epochs and counterbalancing the first order across subjects.

The simulator used was a commercially available driving game, Need for Speed II™ (16). The visual display provided 3D rendering, a rear view mirror, a speedometer, and a view from inside the car looking through

the front window. An LCD projector outside the scanner room and behind the scanner projected through another waveguide to a translucent screen, which the subjects saw via a mirror, attached to the head coil of the fMRI scanner. The screen subtended approximately 25 degrees of visual field. The watching epoch was the same for all subjects (a playback of a previously recorded driving session). For the driving epoch, subjects started at the same point on the track with identical conditions (e.g. car type, track, traffic conditions). They were instructed to stay in the right lane except in order to pass, to avoid collisions, to stay within a speed range of 100-140 (the units were not specified) and to drive normally.

Image Acquisition:

Data were acquired at the FM Kirby Research Center for Functional Brain Imaging at Kennedy Krieger Institute on a Philips NT 1.5 Tesla scanner. A sagittal localizer scan was performed first, followed by a T1-weighted anatomic scan (TR=500ms, TE=30ms, field of view=24cm, matrix=256 x 256, slice thickness=5mm, gap=0.5mm) consisting of 18 slices through the entire brain including most of the cerebellum. Next, we acquired the functional scans consisting of an echo-planar scan (TR=1s, TE=39ms, field of view=24cm, matrix=64 x 64, slice thickness=5mm, gap=0.5mm) obtained consistently over a 10-minute period per run for a total of 600 scans. Ten "dummy" scans were performed at the beginning to allow for longitudinal equilibrium, after which the simulated driving paradigm was begun.

fMRI Data Analysis

The images were first corrected for timing differences between the slices using windowed Fourier interpolation to minimize the dependence upon which reference slice is used (17,18). Next the data were imported into the Statistical Parametric Mapping software package, SPM99 (19). Data were motion corrected, spatially smoothed with a 8x8x11 mm Gaussian kernel, and spatially normalized into the standard space of Talairach and Tournoux (20). The data were slightly sub-sampled to 3x3x4mm, resulting in 53x63x28 voxels. For display, slices 2-26 were presented.

Independent Component Analysis

The model used for the ICA analysis is depicted in Figure 2. Data from each subject were reduced from 360 to 30 time points using principal component analysis. Data from all subjects were then concatenated and this aggregate data set reduced to 25 time points using PCA, followed by group independent component estimation (21) using a neural network algorithm which attempts to minimize the mutual information of the network outputs (12). Time courses and spatial maps were then reconstructed for each subject, tested using a t-test, and thresholded at $p < 0.00025$ ($t = 4.5$, $df = 14$) (21).

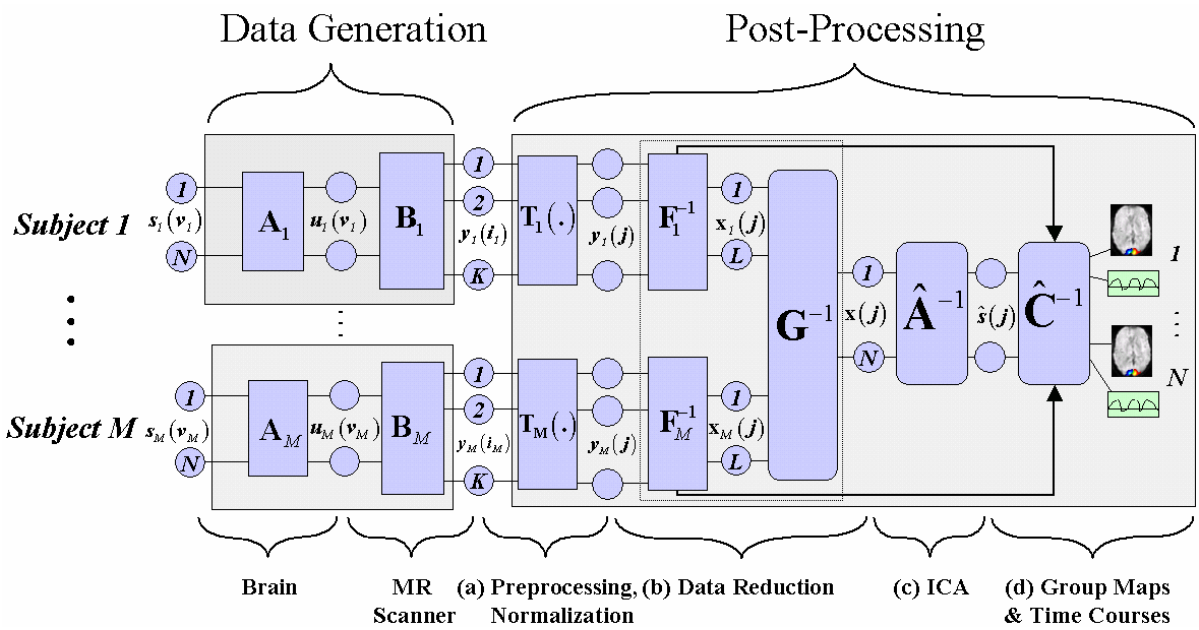

Figure 2: Model for the group ICA analysis. The model indicates our assumptions in the data-generation block and our processing method in the post-processing block. After spatial normalization and reduction, single subject data are combined together, followed by the independent component analysis, and finally individual subject maps and time courses are reconstructed.

RESULTS

Imaging results are summarized in Figure 3, with different colors coding for each component. The fMRI data are comprised of a linear mixture of each of the six depicted components. That is, if a given voxel has a high value for a given component image, the temporal pattern of the data resembles the temporal pattern depicted for that component. Additionally, some areas consist of more than one temporal pattern. For example, the (P) and (B) components overlap heavily in the anterior cingulate and medial frontal regions.

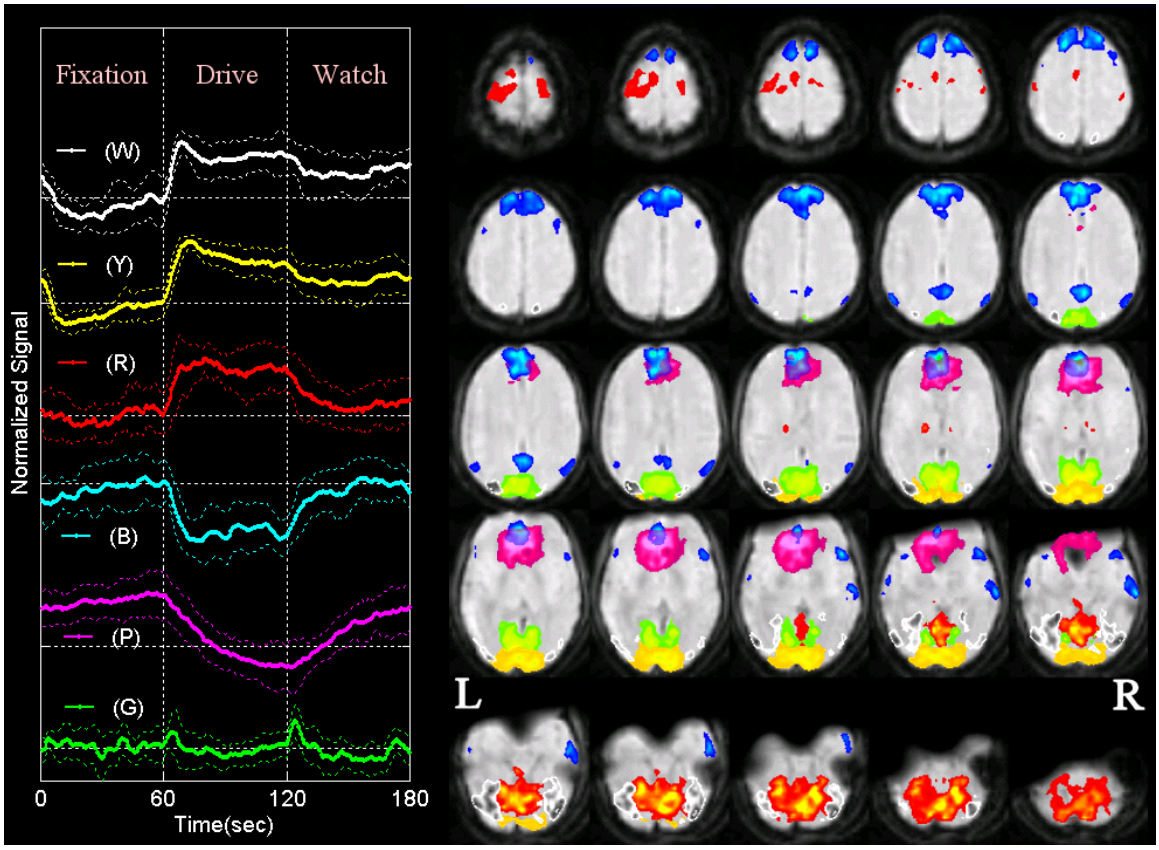

Figure 3: Time courses and Independent Components Derived from functional MRI scans. Random effects group fMRI maps are thresholded at p<0.00025 (t=4.5, df=14). A total of six components are presented. A green (G) component extends on both sides of the parieto-occipital sulcus including portions of cuneus, precuneus, and the lingual gyrus. A yellow (Y) component contains mostly occipital areas. A white (W) component contains bilateral visual association and parietal areas; and a component consisting of cerebellar and motor areas is depicted in red (R). Orbitofrontal and anterior cingulate areas identified are depicted in pink (P). Finally, a component including medial frontal, parietal, and posterior cingulate regions is depicted in blue (B). Group averaged time courses (right) for the fixation-drive-watch order are also depicted with similar colors. Standard deviation across the group of nine subjects is indicated for each time course with dotted lines. The epochs are averaged and presented as fixation, drive, and watch.

The group-averaged time course for the fixation-drive-watch paradigm (with the standard deviation across the fifteen subjects) for each component is presented on the right side of Figure 3, with color use as in the spatial component maps. The three epoch cycles are averaged together and are presented as 'fixation', 'drive', and 'watch'. Each of the time courses depicted was modulated by the driving paradigm.

There were six networks of areas identified. Primary visual (Y) areas, which are know to be involved in processing visual information early on in the visual system. Second, there was involvement of higher order visual/cerebellar (W) areas, which are further downstream from the primary visual areas and involved in motion detection and processing of visuospatial information. A third network identified involved cerebellar/motor (R) areas, which processing motion and motor planning. A network involving anterior cingulate, medial frontal, and other frontal (P) areas was also detected. Such areas are involved in many processing, including inhibition and monitoring and detection of errors. A fifth network identified involved frontoparietal (B) areas, involved in visual attention. Finally, we detected transient visual (G) areas along the occipitoparietal sulcus which are potentially involved in detecting changes in visual input.

These networks demonstrated distinct temporal patterns. Four main patterns are apparent: 1) primary visual (Y) and higher order visual/cerebellar (W) areas were most active during driving and less active during watching (as

compared to fixation) (W,Y), 2) cerebellar/motor (R) and frontoparietal (B) areas were only in(de)creased during driving, 3) anterior cingulate, medial frontal, and other frontal (P) areas demonstrated exponential decrements during driving and rebounded during fixation, and 4) visual (G) areas transiently activated when the driving or watching paradigms were changed.

Examination of the orbitofrontal/anterior cingulate (P) time courses during the driving epoch revealed an exponentially decaying curve, displayed in **Error! Reference source not found.**. This is consistent with the involvement of the orbitofrontal and anterior cingulate involvement in disinhibition (i.e. "taking off the brake") (22,23). The frontoparietal (B) component was decreased during the drive epoch only. This is consistent with an overall increase in vigilance while driving. Previous imaging studies have implicated similar frontal and parietal regions in visual awareness (24).

DISCUSSION

The primary goals of this study were to demonstrate the feasibility of importing a driving simulation environment into an MRI scanner as well as the ability to detect associated brain activation. We designed and implemented a simple simulator environment and decomposed the activation due to a complex behavior into interpretable pieces using a novel, generally applicable approach, based upon independent component analysis. Several components were identified, each modulated differently by our imaging paradigm. Regions that increased or decreased consistently, increased transiently, or which exhibited gradual signal decay during driving were identified.

Future studies will incorporate a programmable simulator as well as a small analog steering wheel, designed to be more realistic and provide smooth driving control. The current controller allows only for small taps to change direction. Additionally, we are actively attempting to correlate our simulator environment with a controlled test road paradigm in an actual car. Certain limitations prevent us from having an ideal simulation environment. For example, since movement of the subjects would corrupt the fMRI data, we can not use a full-size steering wheel to control the car. We will be utilizing a programmable simulator for future studies. This will enable us to do a finer event-related analysis of the fMRI data by correlating the imaging data with certain events such as turns or collisions. Additionally, there are 3D goggles available for an MRI environment and this, combined with an immersive driving software and hardware environment, could provide a more realistic driving experience.

A previous fMRI study involving simulated aviation has found speed-related changes in frontal areas similar to those that we have observed (25). Orbitofrontal cortex has been demonstrated to exhibit fMRI signal change during breaches of expectation (i.e. error detection) in a visual task (26). Our finding of anterior cingulate cortex in the (P) component and *both* anterior and posterior cingulate cortex in the (B) component is consistent with recent studies demonstrating functionally distinct anterior and posterior cingulate regions in spatial attention (27). The frontal and parietal regions identified in the (B) component have also been implicated in attentional tasks involving selected and divided attention (28,29). The angular gyrus, superior parietal gyrus, and posterior cingulate gyrus were also identified in the simulated aviation task. In our study, these areas were contained within the same component and are thus functionally connected to one another; i.e. they demonstrate similar fMRI signal changes, and in that sense are distinct from areas involved in other components.

It is also informative to consider the components identified in the context of their interactions. The overlapping areas of the (B) and (P) components, consisting mainly of portions of the anterior cingulate and the medial frontal gyrus, are indicated in Figure 3. The anterior cingulate has been divided into rostral 'affect' and caudal 'cognition' regions (30), consistent with the division between the (P) and (B) components. Note that activity in the (B) regions decreases rapidly during the driving epoch whereas the (P) regions slowly decrease during the driving condition. One interpretation of these results is that awareness of driving (vigilance) is initiated once the driving condition begins. Error correction and disinhibition are revealed as a gradual decline of this component at a rate determined in part by the vigilance network. During the fast driving condition, the vigilance component changes more; thus the error correction and disinhibition component decreases at a faster rate. Such an interpretation, while consistent with our results, requires further investigation. An EEG study utilizing the NFS simulation software revealed greater alpha power in the frontal lobes during driving than during replay, and was interpreted as being consistent with a reduction of attention during the replay task (31). Our results are consistent with this interpretation, as neither error monitoring nor vigilance is presumably prominent during replay (watching).

Other activated components we observed were consistent with prior reports. For example, the visual association/cerebellar (W) component demonstrates activation in regions previously found to be involved in orientation (32) and complex scene interpretation or memory processing (33). This component also appears to contain areas involved in the modulation of connectivity between primary visual (V2) and motion sensitive visual regions (V5/area MT), such as parietal cortex (Brodmann area 7), along with visual association areas (34). These areas along with the primary visual (Y) areas have been implicated in sensory acquisition (35) and attention/anticipation (36). Activation in both the (W) and (Y) components was increased above fixation during watching and further increased during driving. This is in contrast to (5), but is consistent with sensory acquisition (present in both driving and watching) combined with the attentional and motor elements of driving (present in the driving epoch). That is, the further increase in these areas during driving appears to be an attentional modulated increase (37).

The transient visual (G) areas demonstrate an increase at the transitions between epochs. We identified similar areas, also transiently changing between epochs, in a simple visual task (21). Similar areas have been detected in a meta-analysis of transient activation during block transitions (38) and may be involved in switching tasks in general. The (R) component was mostly in the cerebellum in areas implicated in motor preparation (39). Primary motor contributions were low in amplitude presumably due to the small amount of motor movement involved in controlling the driving task. This would also explain why there was little activation during the watching epoch as during this time motor preparation and visuomotor integration are presumably minimal.

CONCLUSION

In conclusion, it is feasible to study brain activation while engaged in a driving simulation task. It is clear that driving is a complex task. The ability to study, with imaging, a complex behavior such as driving, in conjunction with paradigms studying more specific aspects of cognition, may enhance our overall understanding of the neural correlates of complex behaviors. Future work will focus upon both top-down (as in the current study) and bottom-up (studying individual pieces of driving such as visual attention) to attempt to better understand the neural correlates implicated in driving behavior as well as how these neural processes are affected by alcohol or marinol intoxication.

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