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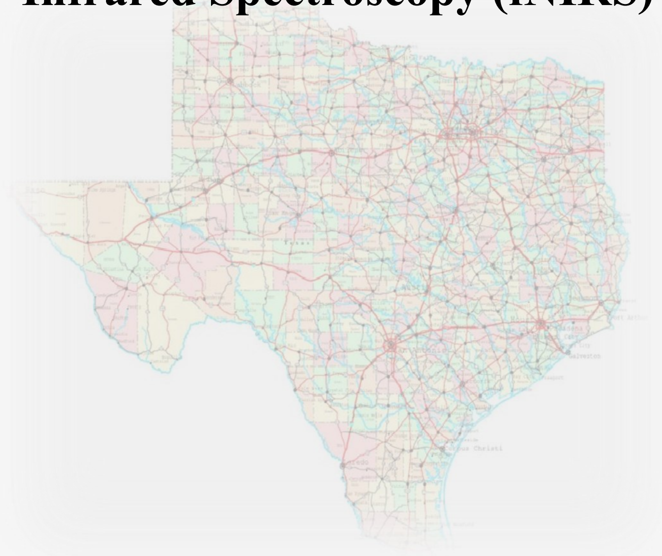
Risk-Taking Behaviors and Prefrontal Cortex Activity of Male Adolescents in the Presence of Peer Passengers during Simulated Driving: A Functional Near-Infrared Spectroscopy (fNIRS) Study



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Risk-Taking Behaviors and Prefrontal Cortex Activity of Male Adolescents in the Presence of Peer Passengers during Simulated Driving: A Functional Near-Infrared Spectroscopy (fNIRS) Study

Report: ATLAS-2015-05

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16. Abstract

Crash statistics show that adolescent drivers are more likely to be involved in motor-vehicle crashes than adults and that the presence of peer passengers pose an additional risk factor for crashes. Experimental and observational studies show that risky driving behaviors of male teenagers increase in the presence of male peer passengers. There could be several mechanisms of the influence of peer passengers on teen drivers, however it is evident that the male teenage driver with a male peer passenger makes riskier decisions than when driving alone, when driving with an adult, or when compared with an adult driver. It has been posited that the developing teenage brain's activity is different from that of adults during decision making, especially in regions associated with impulse control, response inhibition, and risk taking. In order to study risk-taking behavior in simulated driving by male teenagers in the presence of male peer passengers, we leveraged an innovative experimental approach to investigate the brain activity of male teenage and adult drivers while driving alone and in the presence of peer passengers. This study used functional near-infrared spectroscopy (fNIRS) technology, a noninvasive optical brain-imaging method that allows in vivo measurements of oxygenated and deoxygenated hemoglobin in cortical tissue, to study regions in the prefrontal cortex of drivers performing an ecologically valid driving-simulation task. Driving-related risk-taking behaviors were simultaneously measured. In addition, participants undertook a well-validated computerized measure of risk taking (Balloon Analogue Risk Task) as an additional assessment of risk-taking behavior. The results indicate that for certain risky-driving scenarios, adult participants showed increased activation in regions of the left and right medial prefrontal cortex when driving with a passenger as compared with driving alone, whereas these activations were not evident in teenaged drivers in similar situations.

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Abstract

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This study used functional near-infrared spectroscopy (fNIRS) technology, a noninvasive optical brain-imaging method that allows in vivo measurements of oxygenated and deoxygenated hemoglobin in cortical tissue, to study regions in the prefrontal cortex of drivers performing an ecologically valid driving-simulation task. Driving-related risk-taking behaviors were simultaneously measured. In addition, participants undertook a well-validated computerized measure of risk taking (Balloon Analogue Risk Task - BART) as an additional assessment of risk-taking behavior. The results indicate that for certain risky-driving scenarios, adult participants showed increased activation in regions of the left and right medial prefrontal cortex when driving with a passenger as compared with driving alone, whereas these activations were not evident in teenage drivers in similar situations.

Introduction

Background

Motor-vehicle crashes (MVCs) are the leading cause of mortality, as well as a major cause of injury for U.S. teenagers (CDC 2012). Teenage drivers are more likely to experience MVCs than older drivers (NHTSA 2011). MVC risk is higher for male than female, novice, teenage drivers. MVC risk of teenage male drivers is even greater when male teenage passengers are present (Curry et al. 2012; Ouimet et al. 2010), and is associated with a significant increase in the risk of a fatal crash (Chen et al, 2000; Ouimet et al., 2010). There is strong evidence of the effects of peer-passenger influence on teenagers' risky-driving behaviors in naturalistic and driving-simulation studies (Simons-Morton et al, 2011; Ouimet et al., 2013), and findings from brain imaging studies have shown heightened neural activation in brain regions associated with risk-taking and cognitive control in teenagers in the presence of peers (Chein et al, 2011). However, the mechanisms by which teenage passengers result in increased fatal-crash risk for teenage drivers, particularly male teenage drivers, is poorly understood. Brain-imaging research providing data on brain activity during risk taking in the driving context, especially under conditions of peer presence, and in ecologically valid driving-simulation conditions can provide insight into peer influence on teenage risky driving, making the study of brain activation a promising means of understanding the effect of passengers on crash risk of male teenage drivers.

Neural differences in brain development and adolescent risk

Neural-imaging studies suggest that the presence of peers increases adolescent risk taking by heightening neural activation in brain regions associated with reward sensitivity, risk taking, and cognitive control (Chein et al. 2011). Such neuroimaging studies looking at peer influence on teenagers have primarily been conducted using functional magnetic resonance imaging (fMRI) (Chein et al. 2011; Schweizer et al. 2013; Kan et al. 2013) to study brain activation. fMRI, however, has limitations that restrict the study of driving behavior in more realistic conditions, such as in driving simulators. fMRI requires that the study participant be supine, remain unnaturally still, and requires strict absence of metallic objects, thereby imposing serious limitations on the ecological validity of experimental conditions involving driving.

In contrast, functional near-infrared spectroscopy (fNIRS) is a significantly less restrictive and noninvasive imaging technique that uses near-infrared light to monitor brain activation by measuring changes in the levels of oxygenated and deoxygenated hemoglobin (Bunce et al. 2006). While fNIRS is limited in terms of spatial resolution (fMRI allows significantly higher spatial resolution), it has a higher temporal resolution, allowing continuous monitoring of changes in brain activation. fNIRS uses sensors and detectors that can be worn comfortably on headgear by a participant while performing tasks normally, making this approach a viable technique for brain imaging in more ecologically valid conditions, such as during driving (Kojima et al. 2005).

Experimental research on adolescent risk using driving simulation

Driving simulation is highly associated with on-road driving (Fisher et al. 2007) and a safe method for studying driver behavior. Simulator studies have addressed a range of influences on teenage risky-driving behavior, such as distraction (Drews et al. 2008) and passenger attitudes (Ouimet et al. 2013). Simulator studies have shown increased teenage-driver inattention during conversation with peer passengers (White and Caird 2010) and increased risky driving in teen drivers with a peer passenger, even when the peer passenger does not directly interact with the driver (Simons Morton et al., 2013). Studies using lower fidelity driving simulation have reported that teenage risky driving is affected by verbal peer pressure (Gardner and Steinberg 2005; Shepherd et al. 2011), and by being observed by peers (Chein et al. 2011).

This research study was undertaken to better understand the mechanisms of peer influence on male teen drivers by examining activation of specific brain regions of teenagers in a simulated- driving environment. To that end, the study leveraged an experimental approach using driving simulation and fNIRS technology, to assess brain activity in drivers in the presence of peer passengers. This provided an innovative approach to driver-behavior measurement, with functional brain-activation measurements being conducted in vivo and during specific tasks (driving) in an experimental setting. The results of this study will help researchers gain a better understanding of the activity and potential deficits in cognitive processes of the adolescent driver's developing brain. This understanding has the potential to facilitate the development of effective training approaches to reduce the crash risk of novice teenage drivers (Romer, 2010). In addition, the results of this study will advance the use of fNIRS in studying and understanding teenage-driver risk behavior and how to reduce it. Finally, the results of this study provide critical pilot data and evidence of feasibility that will support proposals for larger-scale studies of teenage-driver risk using fNIRS.

Study Approach

Approach

This study was conducted using an innovative approach that leveraged the technologies of *functional near-infrared spectroscopy (fNIRS),* technology that allows measurement of brain activation, in concert with valid and tested driving-simulation methodologies. This study examined risk-taking behaviors of male teens and compared those with risk-taking behaviors of adults both in the presence and absence of a male peer passenger in a simulated-driving environment. The study participants comprised two cohorts grouped by age (teen versus adult), with each participant driving both alone and with an appropriate peer passenger. The flexibility, realism, and ecological validity of the driving-simulation platform allowed the elicitation of natural, driving-related risk behaviors in the participants while simultaneous measurements of appropriate brain regions were conducted.

Experimental data were collected from two sources: driver-behavior measures from a driving simulator and graded changes in oxygenated and deoxygenated blood flow in the brain associated with brain-region activation as measured by fNIRS. Brain-imaging data were collected during the simulated-driving task as well as a standard, behavioral, risk-taking assessment task (Balloon Analog Risk Task - BART). The experimental study was designed to be able to compare brain activation in the prefrontal cortex (PFC) regions of the brain between teen and adult drivers while driving alone versus with a peer passenger. Participants completed realistic driving tasks that required decision making regarding risk outcomes and potential rewards.

Hypotheses

The experiment was designed to examine the following two hypotheses:

1. There will be a significant interaction of age group by passenger condition, such that teenage drivers demonstrate riskier driving behavior in a simulator when driving with a peer passenger compared with driving alone and with adult drivers.

Previous simulator-based studies of teenage drivers have shown higher levels of risky driving behavior when a peer passenger was present (Ouimet et al. 2013; Simons-Morton et al. 2013). However, there is a lack of experimental evidence examining the association between passenger presence and risky driving in adults, although there is epidemiological evidence that passengers are not as much of a risk factor for adults (Chen et al. 2000). Based on this prior research it was anticipated that teenage drivers in the simulator would demonstrate higher levels of risky driving with a passenger present than when driving alone, and that there will be no difference between conditions for adult drivers.

2. Age-group by passenger-condition comparisons will demonstrate differential neural activation in selected PFC regions between groups and conditions resulting in a significant age-group by passenger-condition interaction.

No data are available from prior experimental fNIRS research in the driving domain on which to a priori base directionality of effects or how that might vary across brain regions in terms of risk-taking. However, research on teenage-brain development shows functional differences when compared with adults in the regions that were examined in this study. The direction of effects between adults and teenagers and between passenger conditions was thus explored across selected PFC regions examined in this research.

Driving simulation

Driving simulation is a valid predictor of real-world driving (Fisher et al. 2008), and provides an economical, safe, and robust platform for research such as this. Findings from recent studies using high-fidelity simulators show that social norms have an influence on adolescents' driving behavior. One experiment demonstrated reduced hazard detection by male adolescents when driving with male peer passengers (Ouimet et al. 2013). Another experiment showed that teenage male drivers had more incidents of high-risk driving behavior when they were led to believe that the male passenger in the car was risk-accepting compared with those who were led to believe that the passenger was risk averse (Simons-Morton et al.2014). These and other studies provide motivation and justification for the use of driving-simulation technology to examine driver-risk behavior in teenagers.

A desktop version of UMTRI's driving simulator was used in this study (figure 1). This medium-fidelity RTI (Realtime Technologies Inc.) desktop driving simulator was used to present the virtual driving environment to the participants.

Figure 1 - RTI Desktop Simulator (from simcreator.com)

The simulator consists of a widescreen monitor that displays the virtual driving environment, a steering wheel, and pedals for braking and acceleration. The simulation system runs on RTI's simulation engine, SimCreator, and is highly programmable to create a variety of virtual driving worlds and scenarios. The SimObserver software records objective driving data such as velocity, acceleration, and lane position at 30Hz. The driving simulator was cohoused in a dedicated lab space with the fNIRS equipment at the Center for Human Growth and Development (CHGD) at the University of Michigan.

Brain Imaging: Functional Near-Infrared Spectroscopy (fNIRS)

Near-infrared spectroscopy is an optical method of noninvasively measuring brain activity as indicated by oxygenation of brain tissue (Bunce et al. 2006). Brain activity is fueled by glucose metabolism, so increased neural activity results in increased glucose and oxygen consumption. This results in increased local cerebral blood flow, which carries glucose and oxygen to the active brain areas. The oxygen is transported by oxygenated (O_2Hb) hemoglobin in the blood, and, because oxygen is withdrawn for metabolism of glucose, there is an increase in the volume of deoxygenated hemoglobin (HHb). The optical properties of O_2Hb and HHb in the near-infrared light range (700 – 900 nm) make it possible to measure change in their concentration using optical methods; that is, fNIRS (Obrig et al. 2000). These methods have been successfully employed to study brain activation associated with attention (Derosiere et al. 2013) and working memory (Ehlis et al. 2008); cognitive tasks such as the verbal-fluency task (Herrman et al. 2003) and the Stroop task (Serap et al. 2009); and decision-making behavior tasks such as the Balloon Analog Risk Task (BART) (Li et al. 2013).

This study was carried out at the fNIRS laboratory at the CHGD. A TechEn CW6 fNIRS system was used for measuring hemodynamic changes in participants' brains as they operated the driving simulator (figure 2). This fNIRS system uses a continuous wave approach and can incorporate up to 32 lasers and detectors. The TechEn CW6 system provides real-time data acquisition and real-time display of acquired raw signals for each wavelength and each laser/detector combination that allows for high-speed processing of the raw data output through USB. The system also provides connections for auxiliary signals and triggers for external devices that allow for integration with the driving simulator. The fNIRS equipment provides low-profile, low-weight optical probes, fibers, and headgear. This allows for quick and comfortable setup with high levels of connectivity . The system also allows for customized headgear depending on imaging of specific brain regions. (See section on regions of interest in the Methods subsection.)

Figure 2 - TechEn CW6 fNIRS System (from nirsoptix.com)

Simulator - fNIRS interface

Both the driving simulator and the CW6 fNIRS system were separate experimental systems that this study leveraged in combination for data collection. Given that the neurological data and the driving-simulation data were to be examined in concert, it became necessary for the two systems to be connected and synchronized so as to be able to accurately identify and analyze brain-activity data at certain time points during the simulated drives. The solution for the system interface was reached by sending 5 V triggers to the CW6 system via BNC connectors from the simulator. The 5 V signals were sent via a USB to BNC connection from the driving simulator computers made possible by a Phidget I/O interface (Phidget, Inc, Calgary, Canada). The simulator was programmed to contain trigger points at specified locations or events in the drives (e.g., when the driver entered an intersection). These trigger points marked the instance of an event and also sent a signal to the fNIRS system that was received as a stimulus marker in the fNIRS data and recorded accordingly.

Confederate peer passengers

The experiment was designed such that trained, age-appropriate, male research confederates played the role of the peer passengers. Research confederates were trained to represent the age range of the participants in each of the two age groups. Due to difficulties in recruiting and retaining youthful-looking researchers over the course of the data-collection period, there were a number of confederates of each age group who posed as a peer passenger for participants in that group. A potential limitation in using confederates in lieu of actual friends as peer passengers was that that might result in a reduction in the amount or level of peer influence from confederates. However the use of confederates was best suited for maintaining high levels of experimental control since recruiting real friends has significant potential for introducing various confounds. To maintain close ecological validity, the confederates were chosen such that they closely resembled a member of the relevant peer group. Specifically, the peer confederates for the teen group resembled younger teenagers in terms of clothing and looks, whereas the peer confederates for the adult groups resembled an older population, also achieved by appropriate clothing and selection of confederate age.

Methods

Experimental design

The experiment employed a 2X2 mixed-factorial design with two levels (solo drive and passenger drive) of the within-subject variable (passenger presence) and two levels (male teens and male adults) of the between-subjects variable (driver age). To control for potential order effects, the within-subject drive orders (solo drive first versus passenger drive first) were randomly counterbalanced for both groups, and to minimize any potential carryover effects (of the passenger presence) a washout task was administered to the participants between drives. The University of Michigan IRB approved the experimental protocol, which was based on previous, successful, passenger-condition, driving simulation experiments (Simons-Morton et al. 2013).

Participants

Two groups of drivers were recruited using various techniques including flyers, postings on social and local media, and through driving schools and licensing authorities. The first group comprised 13 male teenagers (16-18 years) who held a Michigan level 2 provisional driver license (independent driving with some restrictions), drove at least twice a week on average, and had their licenses for 4-9 months (see Simons-Morton et al, 2013). The second group comprised 16 young male adults (25-35 years) with a regular driver license, drove at least twice a week on average, and had their licenses for at least 12 months. Teen assent and parental consent were obtained for the participants under age 18, and consent was obtained from those over age 18. Participants were also screened according to specific criteria, such as being neurotypical (i.e., with no diagnosed neurological conditions), not wearing prescription eyeglasses (contact lenses allowed), not currently taking any psychoactive medication, etc. Participants were provided with an incentive of $50 for the roughly 1.5 hour lab visit.

Brain regions of interest

This study used a TechEn CW6 fNIRS system (figure 2) with 690 and 830 nm wavelengths to measure hemodynamic changes in the drivers' brains, and uses a continuous-wave approach incorporating up to 32 lasers and detectors, providing real-time data acquisition and display of raw signals for each wavelength and laser/detector combination. The equipment provides low-profile, low-weight optical probes and fibers that allow quick and comfortable setup for participants. Headgear was customized for this study based on imaging of specific brain regions.

Determination of the regions of interest (ROI) of the brain was made with reference to previous studies of functional activation. fNIRS measurements are limited to the cortical surface, and the limited size of the probes and headgear have additional constraints on the ROIs. Thus, in the current study we set the ROI to encompass the prefrontal cortex (PFC), including the ventrolateral prefrontal cortex (VLPFC), the dorsolateral prefrontal cortex (DLPFC), and the orbitofrontal cortex (OFC), based on their roles in response inhibition (Herrmann et al. 2004), incentive processing and cognitive control (Chein et al. 2010), and risky decision making (Cazzell et al. 2012; Clark et al. 2004).

The final headgear included seven emitters and seven detectors spaced 3 cm apart, yielding 19 data channels sampled at 50 Hz. Optodes were mounted into a custom, 3D-printed headband. Figure 3 shows the probe configuration (letters indicate emitters, numbers indicate detectors) and the placement of the headband on the participant. Brain activation was examined in bilateral prefrontal-cortex regions. The probe localization was established and applied consistently for each participant using the international 10-10 transcranial system positioning (AES 1994). Fz, Cz locations were measured for each participant as anchor points.

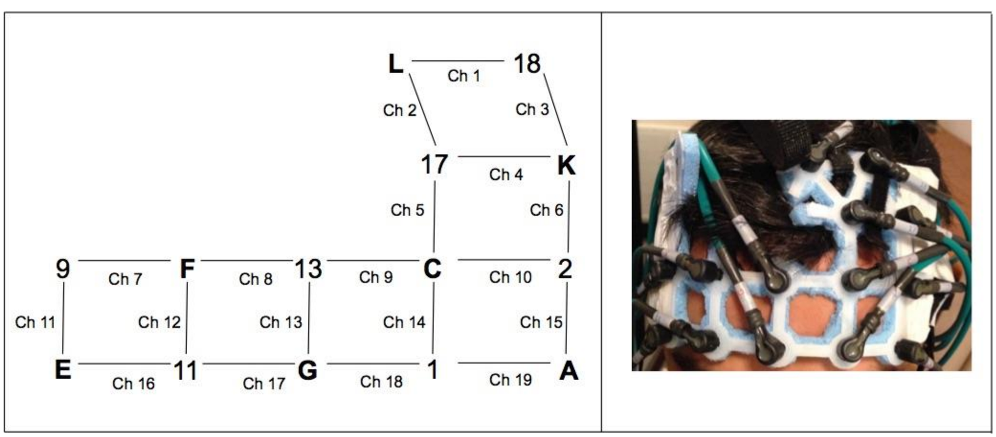

Figure 3 - Probe configuration (with channels numbered) and 3D-printed headband

Procedure

The protocol for the experiment was based on previous, successful, passenger-condition, driving simulation experiments with appropriate modifications for this study (Simons-Morton et al. 2013). Each participant drove the simulator twice, once on his own, and once with the peer passenger (counterbalanced). The drive was designed to elicit natural driving behavior and included scenarios that required risk-relevant decision making that is normal in everyday driving. Participant's brain activations were measured simultaneously during the drives. Due to the experimental evidence in the literature suggesting that the mere presence of a peer may influence driving behaviors of the participants (Simons-Morton et al. 2013), the confederate was trained to solely maintain a presence as a passenger without engaging the driver directly (e.g., no overt pressure, conversation, distracting behaviors).

Each participant started his visit by signing consent (or assent) forms and completing a series of surveys (minor participants brought signed parental consent forms to the visit). The participant was then outfitted with the fNIRS sensors in the main laboratory, a process that included head measurements, fitting of the headgear, and the placement of optodes on appropriate regions of the prefrontal cortex according to a modified international EEG 10-10 system (American Electroencephalographic Society 1994) (figure 4). After the fNIRS sensor calibrations (including ensuring signal detection) the participant was familiarized with the driving simulator via a representative practice drive for about 5 minutes. Laboratory studies have established that this duration of practice is normally sufficient for simulator adaptation (Sahami & Sayed 2013).

If the participant was allocated to the 'solo-drive first' condition, he completed the solo drive before being introduced to the confederate for the passenger drive. If the participant was allocated to the 'passenger-drive first' condition he was introduced to the confederate and complete the passenger drive first and then completed the solo drive. Following all driving tasks, the participants undertook the Balloon Analog Risk Task (BART) while still connected to the fNIRS sensors. A brief survey and debrief period concluded the experiment. Survey items measured demographics, driving behavior and experience (e.g. average miles driven), and perceptions of the peer confederate.

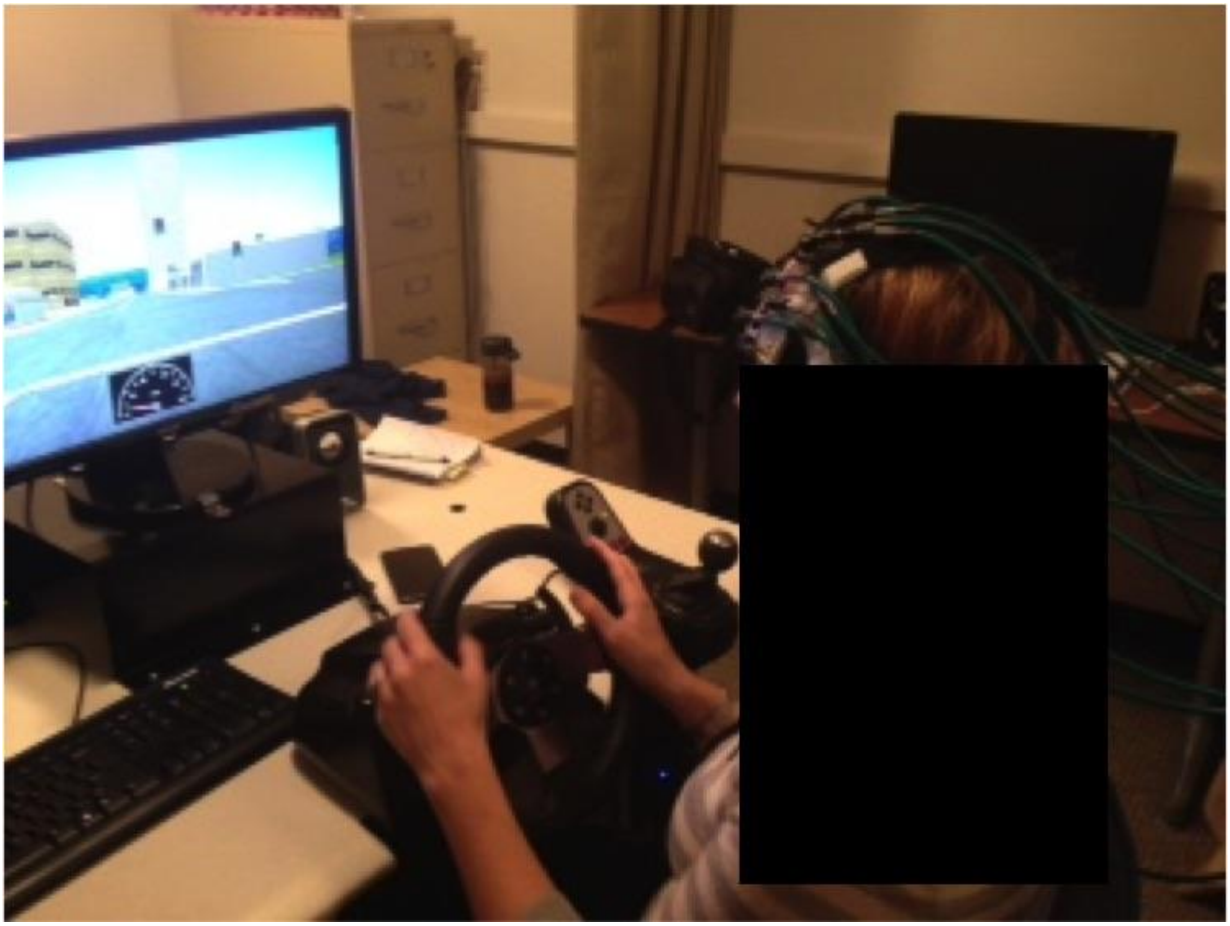

Figure 4 - Driving simulator and participant with fNIRS headgear

The description used to introduce the confederate was based on previously successful procedures (see Simons-Morton et al. 2013) and took place as follows. The experimenter explained to the participant that the confederate was also recruited to be a participant, but because he had to wait for the “other” simulator to be available, the experimenter wanted the confederate to sit with the participant during one of the two experimental drives in order to expose him to the driving simulation task. The confederate was trained and practiced to maintain a friendly but not overly engaging persona. Both the participant and the confederate were instructed to minimize interactions during the experimental drives. During the passenger drive, the confederate was seated to the right of the participant (in the passenger position) and viewed the entire drive without comment. A manipulation check was conducted after the experiment using the debrief survey in order to examine the perception of the participant towards the passenger.

In both the solo and the passenger drives the participant's task was to safely drive to a destination as guided by street signs. Participants were told that the base incentive payment would start at $40 and reaching the destination earlier would result in a bonus in the form of increased payments up to a maximum total of $50. However the breaking of road rules such as running red lights and speeding would result in deductions from the incentive money potentially reducing the payment to as low as $30. Participants were also told that they could make up for lost points by good driving. However, for IRB purposes these addition/deduction calculations were not actually done and all participants were paid $50 at the end of the experiment. When asked, the research assistants conducting the experiment informed the participants that the driving score was automatically computed.

Driving simulation environment

The driving simulator was programmed to provide a realistic driving environment that elicited natural driving behavior. Interspersed within the drive were everyday driving scenarios that required participant to make decisions regarding taking certain risks (such as a dilemma zone involving yellow lights at intersections). The simulated drives were designed such that total driving duration for the two drives did not exceed 30 minutes. This restriction limited exposure to the simulator and hence reduced potential discomfort due to symptoms related to simulator sickness.

The driving environment that each participant was exposed to was designed to contain multiple instances of risk-relevant driving situations. There were three driving worlds that were programmed for this study. The first was a 5-10 minute practice drive that was created to allow participants to get used to operating the driving simulator. The second and the third drives were the experimental drives, each about 10-15 minutes long. The driving worlds contained a daylight setting in a mix of urban, rural, and residential environments and included various roadway geometries, signalized and unsignalized intersections, and ambient traffic and pedestrians (figure 5). The drives also contained realistic roadside elements such as buildings, vegetation, pedestrians, traffic signs, and others. All elements in the driving world were carefully designed and scripted so as to minimize any chance of the driver crashing, losing vehicle control, or any other events that could interrupt the drive.

Figure 5 - Screenshot of driving simulator virtual environment

Of the scenarios that were naturally interspersed in the drives, the primary ones of interest were scenarios that occurred at signalized four-way intersections. There were multiple four-way-signalized intersections that the participant encountered, scripted such that the participant would encounter all phases of the signals (green, yellow, red). Of these, some of the yellow intersections (i.e., the intersections where the light phase changed from green, to yellow, to red) were programmed so as to result in a *dilemma-zone* as the participant approached the scenario. These lights were programmed to change to yellow from green when the participant was at a certain temporal distance or closing distance from the intersection. The temporal distance is a *time to arrival* measure that accounts for distance from the intersection as well as the speed of the vehicle, and thus controls for the speed variability.

The dilemma zones were programmed so that the participants would have to make a quick judgment and decision whether to stop abruptly at a yellow light, or risk entering or being in the intersection when the light was red. This scenario was chosen because it represents a replicable common driving risk, is relevant to driving risk and safety (Gazis, Herman, & Maradudin 1960), and was used in similar simulator experiments examining risky behaviors (Simons-Morton et al. 2014). Each simulated world contained 10 such dilemma-zone signalized intersections occurring along with red-light intersections, or green-light intersections, so that the yellow-light dilemma-zone intersections were encountered in an unpredictable manner and hence could not be anticipated by the participant. For the dilemma-zone situations, the lights were programmed to trigger to yellow from green as the vehicle was 2.3, 2.6, or 2.9 seconds away from the intersection.

Results

Outcome measures

The outcome measures of interest from the simulator were indicators of drivers' risk-taking behaviors during the risk-relevant scenarios interspersed within the driving environment. Specifically, in this case the outcome measures were the driver responses at the yellow dilemma-zone intersections (*events*), i.e., whether a driver stopped or not at a yellow light. The outcome measure from fNIRS was neural activity measured by changes in concentration of oxygenated hemoglobin (O2Hb), deoxygenated hemoglobin (HHb), and total hemoglobin (HbT) during specific events in the simulation at specified prefrontal cortex areas. In particular, neural activity was analyzed for each yellow-light-dilemma intersection event before the driver saw a yellow signal.

Survey results

Teen Participants

Teen participants had median age of 16 years (n=7, 58.3%) and there were an additional five teens age 17 years (41.6%). All participants identified as being white, with the exception of two participants who identified as being of Asian background. They were primarily in eleventh grade (n= 11, 92.3%); some were in tenth grade (n= 1) and twelfth grade (n= 1). Students identified that they received mostly A grades (n= 6, 46.2%) or mostly A's and B's (n= 6, 46.2%), followed by mostly B and C grades (n= 1, 7.7%). Two participants reported that they were taking medications, one for treating asthma and one for treating pain. There were no reports of taking medications for depression or anxiety, diabetes, or Attention-Deficit/Hyperactivity Disorder (ADD/ ADHD).

Typically participants' parents received some post-high-school education, with 38.5% of mothers receiving a graduate degree (n=5), 53.8% receiving a four-year college degree (n=7), and one having a trade-school education. With regard to fathers, 46.2% received a graduate degree (n=6), 30.8% received a four-year college degree (n=4), and two claimed a high-school education as the highest formal-education qualification. One other had a trade school or associate degree. As a measure of social standing, teens reported (on a 10-point scale) where they believed they ranked in their community. The mean social standing was 7.27 (SD =1.27). They were then asked to repeat the measure but instead rank their standing within the U.S.. The mean ranking was 6.92 (SD= 1.32). This is consistent with other research projects of teens of a similar demographic (Simons-Morton et al. 2013).

Participants were recently licensed (median = 5 months, mean = 5.25 months, range 4-8 months). More often they were the sole driver of a vehicle (n= 7, 53.8%) ; 46.2% reported they shared the vehicle (n=6). The teens reported driving regularly: 46.2% drive every day (n=6), 23.1% drove five or six times per week (n=3), 30.8% drove three or four times per week (n=4). Two participants had been in a crash since receiving their level 2 license. One of these two reported that he had been pulled over by police and another two participants also reported that they had been pulled over by police since obtaining their licenses. None of these three reported that they had received a ticket. Teens reported on their resistance to peer pressure and the mean score of resistance to peer pressure was 2.15 (SD=.29, possible range 1-4).

Teens also reported on their perceptions of the confederate on a scale of 1-3; Yes, Maybe, No. They reported the degree to which they would like to get to know him (mean = 2.23, SD = .60), were like him (mean = 1.92, SD = .64), and the degree to which he'd be liked by the participant's parents (mean = 1.92, SD =.64). They were also asked the degree to which they liked the confederate (mean = 1.92, SD = .64), and that he would fit in with the participant's friends (mean = 2.09, SD = .64) and be someone they would like to hang out with (mean = 2.38, SD = .51). Overall mean score of identification with the passenger was 2.07 (SD=.46).

Further, participants rated the likelihood that the confederate would be someone who performs risky driving behaviors on a scale of 1-5 (1 – Very unlikely, 5 – Very likely), including going through a yellow light at an intersection (mean = 3.38 SD = 1.33), passing a vehicle that is going the speed limit (mean = 3.08, SD = 1.38), following a vehicle too closely (mean = 2.54, SD = 1.3), and stopping at a yellow light (mean = 2.85, SD = 1.46). Overall mean score for the passenger risky-driving measure was 2.92 (SD=.76).

Adult Participants

Adult participants had a mean age of 27.44 years (SD=2.22, 27 years was the median age) with ages ranging from 25 to 32 years. Most participants identified as being white (n=10, 62.5%),two participants identified as black (12.5%) and three participants identified as being both black and white (18.8%), and one participant identified as being of Asian background. Two participants reported that they were taking medications, one for treating asthma and one for treating pain. There were no reports of taking medications for depression or anxiety, diabetes, pain, or ADD/ ADHD.

Typically participants' received some post-high-school education: 25% received a post-graduate degree (n=4), one received graduate or professional training, 50% received a four-year college degree (n=8), and three had some college education (18.8%). As a measure of social standing, adults also reported (on a 10-point scale) where they believed they ranked in their community. The mean social standing was 6.06 (SD = 2.11). They were then asked to repeat the measure but instead rank their standing within the United States, the mean ranking was 5.94 (SD= 2.08).

Participants reported driving regularly: 56.3% drive every day (n=9), 18.8% drive five or six times per week (n=3), 12.5% drive three or four times per week (n=2), and 12.5% drive one or two days per week (n=2). One participant had been in two crashes in the past year, but had not been pulled over by police for any moving violations. There were four participants who reported that they had been pulled over by police for a violation. Two of these participants had the one occasion of a moving violation yet only one had received a ticket and two of these participants had three occasions, all but one of these occasions a ticket was received.

Adult participants also reported on their perceptions of the confederate. They reported the degree to which they would like to get to know him better (mean = 2.13, SD = .72), they liked him (mean = 2.13, SD = .74), and the degree to which he would be liked by the participant's parents (mean = 2, SD = .38). They were also asked the degree to which he was like the participant (mean = 2.27, SD = .59), would fit in with the participant's friends (mean = 2.07, SD = .59), and would be someone they would like to hang out with (mean = 1.93, SD = .46). Overall mean score of identification with the passenger was 2.13 (SD=.41).

Further, participants rated the likelihood that the confederate would be someone who performs risky-driving behaviors, including speeding (mean = 2.8, SD = .86), going through a yellow light at an intersection (mean = 3.5, SD = .73), passing a vehicle that is going the speed limit (mean = 3.0, SD = .85), following a vehicle too closely (mean = 2.3, SD = .72), and stopping at a yellow light (mean = 2.6, SD = .82). Overall mean score for the passenger risky driving measure was 2.93 (SD=.48).

Driving simulation results

Driving behavior at risk-relevant scenarios of interest was compared for each group when driving alone versus when driving with a peer passenger. Specifically, the percentage of yellow-light intersections that the participant stopped at was compared within subjects for the solo-drive condition and the passenger-drive conditions for both groups. For both groups there were no significant differences in the stopping behaviors between the solo- and passenger-drive conditions (Adults: percentage stopped=0.11 with passenger; =0.15 without passenger; $p = 0.10$; Teens: percentage stopped=0.15 with passenger; =0.16 without passenger; $p = 0.10$).

fNIRS analytical approach

The brain-activity imaging data from the fNIRS system were preprocessed using the Homer2 tool (Huppert et al. 2009), a MATLAB-based software. The following preprocessing steps were carried out in the order presented: data preexamination, optical-density-change data conversion, data detrending, filtering, and concentration-change data conversion. The raw-time course data were then converted into units of optical-density change (ΔOD). Data then went through a detrending process. Finally, a low-pass filter with cutoff frequency at 0.5 Hz was applied to the ΔOD data, and the hemoglobin-concentration-change data were calculated using the modified Beer-Lambert law, which yielded O2Hb and HHb values. Only O2Hb values were analyzed in this study, due to previous evidence showing its consistency in revealing brain activation (Lin et al. 2009; Xiao-Su et al. 2010).

Each participant's hemoglobin concentration data from multiple events from two driving sessions (solo and passenger) were analyzed using an event-averaging algorithm based on stimulus markers programmed at each event. The time range selected for averaging started 6 seconds before an intersection was reached (this window incorporated the onset of the yellow light) and was 16 seconds long to allow for sufficient measurement of changes in blood flow. Finally, the derived, averaged, time series from two driving sessions were compared using a two-tailed t-test ($p < 0.05$).

fNIRS results

The fNIRS data were analyzed separately for the two groups, essentially comparing brain-activation levels before and at the events of interest for the two within-subject conditions (solo drive and passenger drive).

For the adult participants, the analyses showed statistically significant differences in brain-activation levels in various regions of interest based on passenger condition. In particular, when the light turned yellow, adult drivers showed higher brain activity in the left medial prefrontal cortex (Channels 7, 8, 12) and right medial prefrontal cortex (channels 9,10,14,15) while driving with a passenger, as compared with driving alone (See figure 8 for an example of the activity in one channel).

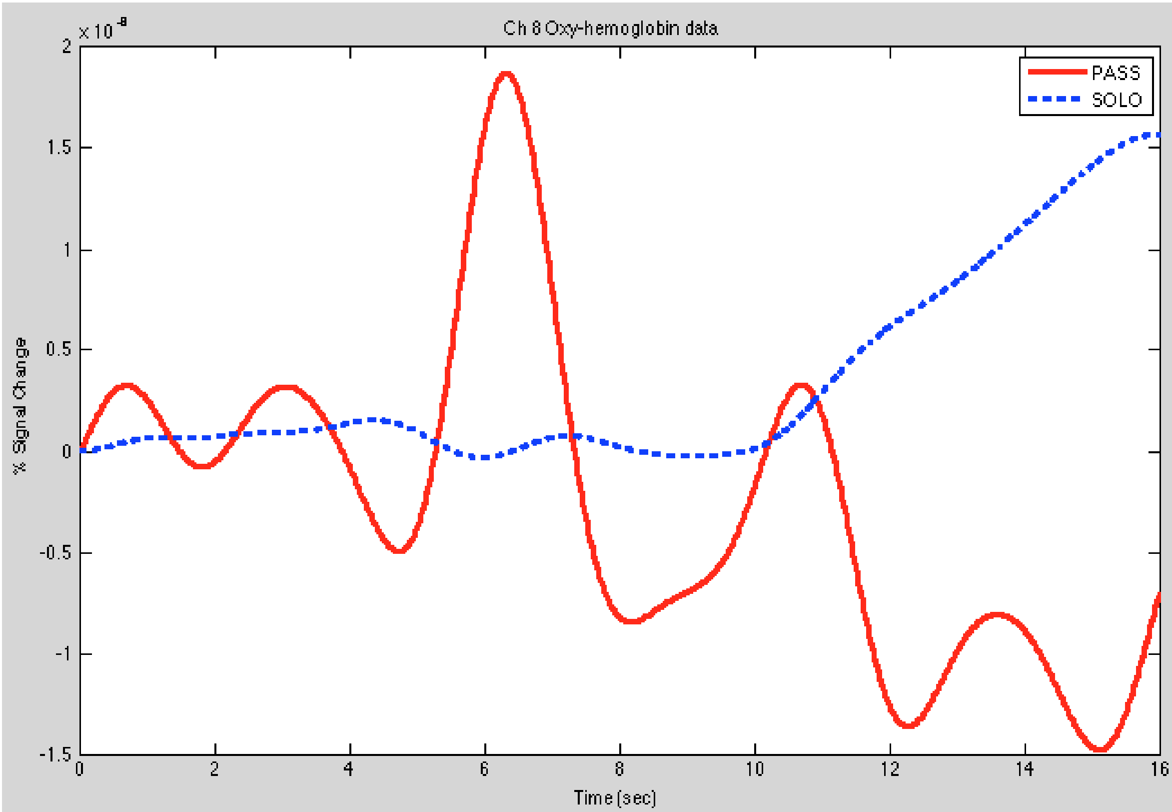

Figure 6 - Averaged hemodynamic response for channel 8 (Adults)

On the other hand, similar analyses for the teen participants showed no statistically significant differences in brain-activation levels in the regions of interests based on passenger condition. When the light turned yellow, teen drivers did not have a significantly different level of brain activity while driving with a passenger as compared with driving alone. (See figure 9 for an illustration of the teen's brain activity for an example channel).

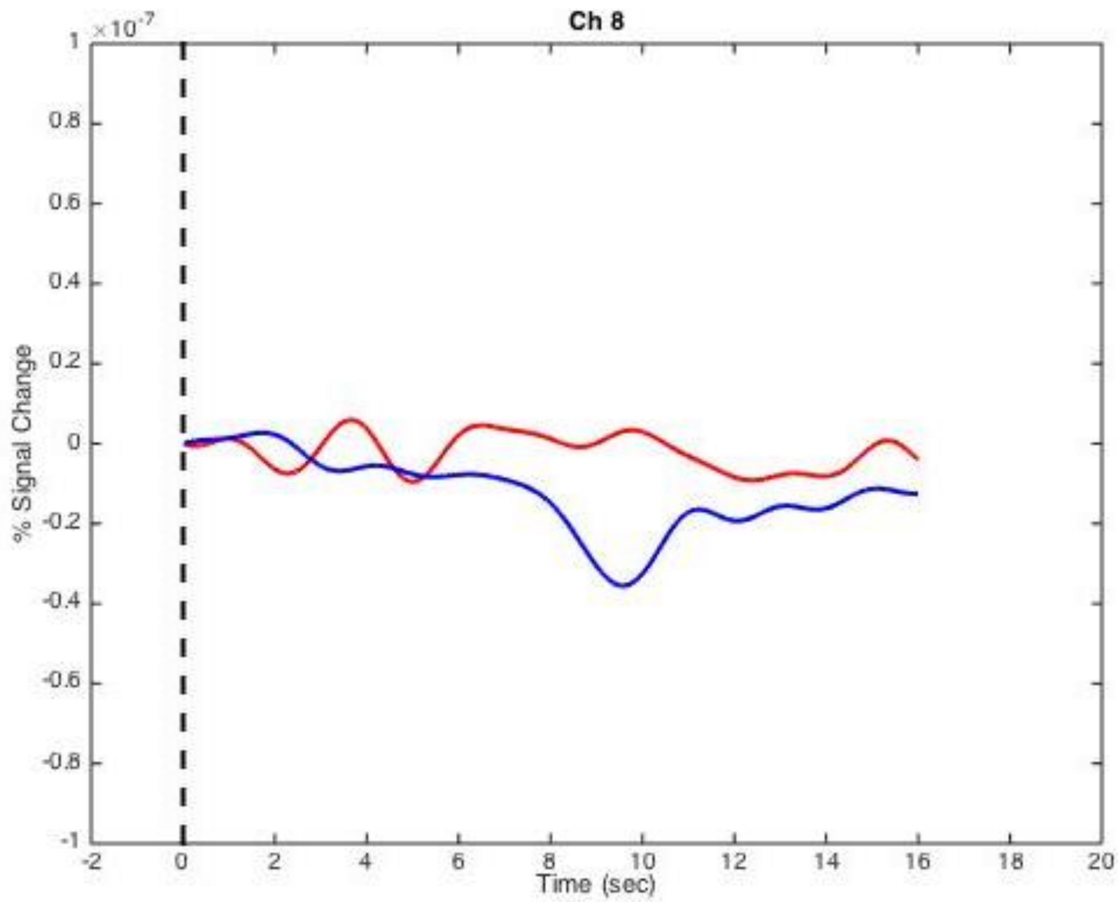

Figure 7 - Averaged hemodynamic response for channel 8 (for teens)

Conclusions/Discussion

This study was conducted as a proof of concept to test the feasibility of measuring functional brain activity using fNIRS in drivers during an ecologically valid task. The intent was to understand the applicability of the fNIRS measurements to a task such as driving and to understand if using fNIRS during such tasks would result in artifacts from motion or other unexpected sources. The study also examined specific brain activity in defined regions of interest during specific driving events to understand differences in solo driving versus driving with passengers in teenagers and adults. Thus, this study used fNIRS technology to measure brain activity in the prefrontal cortex of both teen and adult drivers during a simulated driving task, with and without a passenger.

Accordingly, there are two broad sets of conclusions that can be drawn from this study.. One is the question about feasibility of this experimental approach as a means to examine driving behavior with a reasonably high degree of ecological validity using brain-imaging metrics. By most measures, the data and the experiences from the project indicate that the methodology is indeed viable. Convergence of driving simulation and fNIRS technologies yielded a novel set of data that allowed functional evaluation of brain activity during experimental tasks that were close to real world tasks. This study tested the feasibility of using fNIRS to measure brain activation in a simulated-driving environment. The findings establish feasibility of this approach to studying driver behavior, including selection of brain ROI and understanding potential limitations. Thus, it lays the groundwork for further research with higher levels of ecological validity, including test-track or naturalistic driving. These findings provide foundational evidence that can be used in future studies of neural activation in drivers, especially adolescents. The results of this study support the use of fNIRS in studying driver behavior and provide critical pilot data that support larger-scale studies of driver risk using this methodology and approach.

The second is with respect to the results yielded from the analyses of the collected data. Although this is a preliminary proof-of-concept study, it is the case that the methodologies and the experimental design resulted in data that indicate discrimination between passenger conditions for teen and adult groups. The results show that adult drivers did not behave differently. That is, they did not stop less or more frequently at yellow intersections regardless of whether they drove alone or with a passenger. However, the neural data show significantly higher activation in the left and right medial prefrontal cortices when approaching a yellow light when the participants drove with a passenger. Studies have shown these areas to be associated with active, risky, decision making (Rao et al. 2008), voluntary decision making (Cazzell et al. 2012), and response inhibition (Rubia et al. 2003). Thus, despite no outward (simulator-measured) behavioral evidence of specific driving decisions, the data suggest active differences in neural processing during these scenarios. This is however not the case for the data from the teen drivers. Similar to the adults, the teen drivers also did not show differences in driving behavior at the yellow-light intersections, regardless of passenger presence. However, unlike the adult drivers, the teen drivers did not show any significant difference in brain activity in the prefrontal cortex regions of interest when approaching a yellow light, nor whether the driver was with a peer passenger or he drove alone. No data are available from prior experimental fNIRS research in the driving domain on which to base directionality of effects or how that might vary across brain regions in terms of risk taking or age characteristics. However, neuroscience research on teenage brain development has shown functional differences when compared with adults in the regions that were examined in this study. Further fNIRS experiments can extend those findings. Despite limitations of small sample size and somewhat lower ecological validity, the result is promising and offers new insight into neural activation in adults based on passenger condition.

Recommendations/Future Steps

Driver-behavior measurement in a simulated-driving environment was somewhat limited by the level of ecological validity of the desktop simulation environment in this study. Although desktop-based driving-simulator setups have been utilized in clinical and other settings (e.g., Lew et al. 2005), the level of fidelity was lower compared with full-cab driving-simulator systems. However the results of this study will help establish the feasibility of such an approach to measuring brain activity to understand driver behavior, including selection of brain areas of interest and understanding potential limitations imposed by motion. This will lay the groundwork for further study of driving behavior in environments offering higher levels of ecological validity, whether they be on testtracks or during naturalistic driving.

While the project provides the seed data for large-scale research, the pilot data themselves provide important new information and yield an opportunity for dissemination of new understandings of the mechanisms by which teen drivers are affected by passengers. Teenage drivers are at a higher risk of motor-vehicle crashes compared with adult drivers, and this risk is highest during early independent driving. Research has suggested that crash risk is elevated due to teen immaturity and inexperience and increases with the presence of teenage passengers. Little is known, however, about the processes by which this influence operates. This research provides a foundation knowledge that, through effective dissemination, can expand knowledge in this area. This research also has the potential to inform subsequent projects and eventually inform design and implementation of interventions and policy related to reducing teen-driver crash risk.

References

American Electroencephalographic Society. 1994. American Electroencephalographic Society. Guideline thirteen: guidelines for standard electrode position nomenclature*. J Clin Neurophysiol. 11:111–113.*

Bunce, S. C., Izzetoglu, M., Izzetoglu, K., Onaral, B., & Pourrezaei, K. (2006). Functional near-infrared spectroscopy. *IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society, 25(4), 54–62.*

Cazzell, M., Li, L., Lin, J.Z., Patel, S.J. & Liu, H. (2012), "Comparison of neural correlates of risk decision making between genders: an exploratory fNIRS study of the Balloon Analogue Risk Task (BART)," *Neuroimage, 62(3), 1896-911*

Centers for Disease Control and Prevention & National Center for Injury Prevention and Control. (2012). Web-based Injury Statistics Query and Reporting System (WISQARS). *http://www.cdc.gov/injury/wisqars/index.html.*

Chen, L. H., Baker, S. P., Braver, E. R., & Li, G. (2000). Carrying passengers as a risk factor for crashes fatal to 16- and 17-year-old drivers. *The Journal of the American Medical Association, 283(12), 1578-1582.*

Chein, J. M., Albert, D., O'Brien, L., Uckert, K., & Steinberg, L. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science, 14(2), F1-F10.*

Clark, L., Cools, R., & Robbins, T.W. (2004), "The neuropsychology of ventral prefrontal cortex: decision-making and reversal learning," *Brain Cogn, 55(1), 41-53*

Curry, A. E., Mirman, J. H., Kallan, M. J., Winston, F. K., & Durbin, D. R. (2012). Peer passengers: How do they affect teen crashes? *Journal of Adolescent Health, 50(6), 588-594*.

Derosière, G., Billot, M., Ward, E. T., & Perrey, S. (2013). Adaptations of Motor Neural Structures' Activity to Lapses in Attention. *Cerebral cortex (New York, N.Y. : 1991), 1–9. doi:10.1093/cercor/bht206*

Drews, F. A., Pasupathi, M., & Strayer, D. L. (2008). Passenger and cell phone conversations in simulated driving. *Journal of Experimental Psychology: Applied, 14(4), 392-400. doi:doi:10.1037/a0013119*

Ehlis, A.-C., Bähne, C. G., Jacob, C. P., Herrmann, M. J., & Fallgatter, A. J. (2008). Reduced lateral prefrontal activation in adult patients with attention-deficit/hyperactivity disorder (ADHD) during a working memory task: a functional near-infrared spectroscopy (fNIRS) study. *Journal of psychiatric research, 42(13), 1060–7. doi:10.1016/j.jpsychires.2007.11.011*

Fisher, D. L., Pradhan, A. K., Pollatsek, A., & Knodler, M. A. (2007). Empirical evaluation of hazard anticipation behaviors in the field and on driving simulator using eye tracker. *Transportation Research Record, 2018, 80-86.*

Gardner, M., & Steinberg, L. (2005). Peer Influence on Risk Taking, Risk Preference, and Risky Decision Making in Adolescence and Adulthood: An Experimental Study. *Developmental Psychology, 41, 625-635.*

Gazis, D., Herman, R., & Maradudin, A. (1960). The problem with the amber signal light in traffic flow. *Operations Research, 8*(1), 112-132.

Herrmann, M. J., Ehlis, a.-C., & Fallgatter, a. J. (2003). Frontal activation during a verbal-fluency task as measured by near-infrared spectroscopy. *Brain Research Bulletin, 61(1), 51–56. doi:10.1016/S0361-9230(03)00066-2*

Herrmann MJ, Plichta MM, Ehlis AC, & Fallgatter AJ.(2005) Optical topography during a Go-NoGo task assessed with multi-channel near-infrared spectroscopy. *Behav Brain Res 2005;160:135–40*

Huppert, T.J., Diamond, S.G., Franceschini, M.A., & Boas, D.A. (2009). HomER:a review of time-series analysis methods for near-infrared spectroscopy of the brain*. Appl Opt 48,10:D280-98.*

Johnston, L. D., O'Malley, P. M., Bachman, J. G., & Schulenberg, J. E. (2005). Monitoring the future: National survey results on drug use, 1975-2004. Volume I: Secondary school students*. NIH Publication 05-5727. Bethesda, MD: National Institute on Drug Abuse*.

Kan, K., Schweizer, T. a, Tam, F., & Graham, S. J. (2013). Methodology for functional MRI of simulated driving. *Medical physics, 40(1), 012301*

Kojima, T., Tsunashima, H., Shiozawa, T., & Takada, H. (2005). Measurement of train driver's brain activity by functional near-infrared spectroscopy (fNIRS).*The Second Asian and Pacific Rim Symposium on Biophotonics, 2004. APBP 2004.*

Lew, H. L., Poole, J. H., Lee, E. H., Jaffe, D. L., Huang, H.-C., & Brodd, E. (2005). Predictive validity of driving-simulator assessments following traumatic brain injury: a preliminary study. *Brain Injury, 19(3), 177–188. doi:10.1080/02699050400017171*

Li, L., Lin, Z., Cazzell, M., & Liu, H. (2013). Test-retest assessment of functional near-infrared spectroscopy to measure risk decision making in young adults. *In N. Kollias, B. Choi, H. Zeng, H. W. Kang, B. E. Knudsen, B. J. Wong, … M. D. Morris (Eds.), Proc. of SPIE (Vol. 8565, pp. 856557–1–7). doi:10.1117/12.2005552*

Lin, PY, Lin, SI, Penney, T, & Chen J. (2009) Review: applications of near infrared spectroscopy and imaging for motor rehabilitation in stroke patients. *J Med Biol Eng, 2009*

National Highway Traffic Safety Administration. (2011). *Traffic Safety Facts 2009: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System* (HS-811 402). Washington, DC: U.S. Department of Transportation.

Obrig, H., Wenzel, R., Kohl, M., Horst, S., Wobst, P., Steinbring, J., Thomas, F., & Villringer, A., (2000) Near-infrared spectroscopy: does it function in functional activation studies of the adult brain, *Int. J. Psychophysiol. 35, 125–142.*

Ouimet, M. C., Pradhan, A. K., Simons-Morton, B. G., Divekar, G., Mehranian, H., & Fisher, D. L. (2013). The effect of male teenage passengers on male teenage drivers: Findings from a driving simulator study. *Accident Analysis & Prevention, Volume 58, September 2013, Pages 132–139*

Ouimet, M. C., Simons-Morton, B. G., Zador, P. L., Lerner, N. D., Freedman, M., Duncan, G. D., & Wang, J. (2010). Using the U.S. National Household Travel Survey to estimate the impact of passenger characteristics on young drivers' relative risk of fatal crash involvement. *Accident Analysis & Prevention, 42, 689-694.*

Rao, H., Korczykowski, M., Pluta, J., Hoang, A., & Detre, J. A. (2008). Neural correlates of voluntary and involuntary risk taking in the human brain: an fMRI Study of the Balloon Analog Risk Task (BART). *Neuroimage*, *42*(2), 902-910.

Rubia, K., Smith, A. B., Brammer, M. J., & Taylor, E. (2003). Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *Neuroimage*, *20*(1), 351-358.

Romer, D. (2010). Adolescent risk taking, impulsivity, and brain development: Implications for prevention. *Developmental Psychobiology, 52, 263–276. doi:10.1002/dev.20442*

Sahami, S., & Sayed, T. (2013). How drivers adapt to drive in driving simulator, and what is the impact of practice scenario on the research? *Transportation Research Part F: Traffic Psychology and Behaviour, 16, 41–52. doi:10.1016/j.trf.2012.08.003*

Schweizer, T. a, Kan, K., Hung, Y., Tam, F., Naglie, G., & Graham, S. J. (2013). Brain activity during driving with distraction: an immersive fMRI study. *Frontiers in human neuroscience, 7(February), 53*

Serap, S., Tapsin, M., & Akin, A. (2009). Investigating brain hemodynamics of ADHD patients by functional near infrared spectroscopy. Conference proceedings : ... *Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference, 2009, 3028–30. doi:10.1109/IEMBS.2009.5333293*

Shepherd, J. L., Lane, D. J., Tapscott, R. L., & Gentile, D. A. (2011). Susceptible to Social Influence: Risky "Driving" in Response to Peer Pressure. *Journal of Applied Social Psychology, 41(4), 773-797.*

Simons-Morton, B.G., Bingham, C.R., Falk, E.B., Li, K., Pradhan, A.K., Ouimet, M.C., Almani, F., & Shope, J.T. (2013) Experimental Effects of Injunctive Norms on Simulated Risky Driving Among Teenage Males. *Health Psychology, 33(7), 616.*

White, C. B., & Caird, J. K. (2010). The Blind Date: The effects of change blindness, passenger conversation and gender on looked-but-failed-to-see (LBFTS) errors. *Accident Analysis and Prevention, 42(6), 1822-183*

Xiao-Su, H., Keum-Shik H., Shuzhi S. G., & Myung-Yung, J., (2010) Kalman estimator- and general linear model-based on-line brain activation mapping by near-infrared spectroscopy. *BioMedical Engineering OnLine 2010 9:82.*