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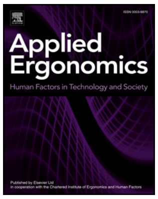

Mental workload is reflected in driver behaviour, physiology, eye movements and prefrontal cortex activation

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ABSTRACT

Mental workload is an important factor during driving, as both high and low levels may result in driver error. This research examined the mental workload of drivers caused by changes in road environment and how such changes impact upon behaviour, physiological responses, eye movements and brain activity. The experiment used functional near infrared spectroscopy to record prefrontal cortex activation associated with changes in mental workload during simulated driving. Increases in subjective ratings of mental workload caused by changes in road type were accompanied by increases in skin conductance, acceleration signatures and horizontal spread of search. Such changes were also associated with increases in the concentration of oxygenated haemoglobin in the prefrontal cortex. Mental workload fluctuates during driving. Such changes can be identified using a range of measures which could be used to inform the development of in-vehicle devices and partially autonomous systems.

1. Introduction

Driving has been described as involving extreme fluctuations in mental workload (Baldwin and Coyne, 2003; Verwey, 2000). A number of factors such as: interaction with in-vehicle devices (Koo et al., 2009), distractions from passengers (Regan and Mitsopoulos, 2001) and changes in driving demands, for instance variations in traffic and pedestrian density (de Waard, 1996) can impact upon a driver's mental workload. The influence that such changes have on the vehicle operator are important to understand with increases in in-vehicle systems and ongoing development of autonomous systems. This is because both high and low levels of mental workload have been shown to lead to inaccurate perceptions, low levels of attention, and insufficient time for accurate information processing (Brookhuis and De Waard, 2001; Pereira and Silva, 2014). This in turn may lead to operator error, a factor accountable for up to 90% of road traffic collisions (Sabey and Staughton, 1975).

Mental workload is typically seen as the amount of operator resources that are required to meet task demands (Eggemeier et al., 1991). The ability to detect changes in mental workload is important in ergonomic research and there are three dominant techniques which have previously been implemented to measure driver workload. These measures are driver behaviour, physiological responses and subjective ratings. One technique that has not yet been fully explored is to record the brain activity of drivers in relation to mental workload changes. The importance of including higher-level cognitive measures during driving assessment as well as relatively low-level vehicle control measures has been noted (Underwood et al., 2011).

Brain activation during driving has previously been difficult to examine due to techniques being unsuited for use in ecologically valid environments. However, recent advances in neuroimaging techniques have made it possible to measure brain activity in environments such as simulated and on-road driving without posing any additional risk or restriction to the participant. One such technique is functional near infrared spectroscopy (fNIRS). fNIRS uses near infrared light to record changes in the concentration of oxygenated and deoxygenated haemoglobin from a resting baseline measure. It overcomes many of the issues associated with other neuroimaging techniques, such as lack of portability and extremely high sensitivity to motion artefacts.

Previous research suggests that brain activation can be used as an index of mental workload. Specifically, the prefrontal cortex (PFC) is an area of the brain that has been shown to reflect changes in mental workload in a laboratory environment (Molteni et al., 2008; Sassaroli et al., 2008) and can be measured using fNIRS. Research conducted in simple laboratory settings typically shows increases in oxygenated and decreases in deoxygenated haemoglobin with increases in workload, as manipulated using tasks such as the n-back and Stroop (Ciftçi et al., 2008; Sassaroli et al., 2008). The limited research in a driving context has shown activation of the PFC during driving (Shimizu et al., 2011). Furthermore, increases in mental workload during driving have been

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associated with changes in PFC activation (Sibi et al., 2016; Unni et al., 2016), often with contrasting results. For example, Wortelen et al. (2016) reported that fNIRS data correlated well with the difficulty of a secondary n-back workload task during simulated driving, with increases in deoxygenated haemoglobin concentration associated with increased workload (results for oxygenated haemoglobin were not reported in this experiment). As with much of the mental workload and driving research, this experiment used a secondary task to manipulate workload. More natural manipulations caused by changes in road width (Shimizu et al., 2009) or the introduction of automatic cruise control (Tsunashima and Yanagisawa, 2009) have also shown changes in PFC activation with proposed mental workload changes. More specifically, Tsunashima and Yanagisawa (2009) reported increases in oxygenated haemoglobin and decreases in deoxygenated haemoglobin with increased workload.

In an experimental context, there are a number of techniques that can be used to manipulate a driver's mental workload. As there is a proposed relationship between task demand, mental workload and performance (Parasuraman and Hancock, 2001; de Waard, 1996; Young and Stanton, 2002) alterations to the task itself are typically used to manipulate workload. As mentioned, one such technique is the addition of a secondary task during driving. For example, Lansdown et al. (2004a,b) reported that increases in secondary task demands had a detrimental effect on driving behaviour, including reduced headway and increased braking pressure (harsher braking).

Secondary tasks and their associated changes in behaviour may be reflective of the workload experienced and behaviours observed when drivers engage in other tasks, such as conversing or interacting with in-vehicle devices during driving. However, it is important to understand how changes in the primary driving task affect mental workload and driving behaviour. Furthermore, the inclusion of a secondary task creates an additional issue in that it is difficult to determine whether the primary or secondary task receives priority with regards to operator resources. Previous research has shown changes in behaviour as a result of manipulations of the primary driving task. For example, Lee and Triggs (1976) and Martens and van Winsum (2000) found that when driving through more complex, busy traffic, and narrow curves there was an increased reaction time and reduced hit rate in a peripheral detection task when compared to driving through less complex residential roads. The increasing task demand and thus mental workload caused by complex environments can impair performance even before other potential problems such as in-vehicle systems are considered. Although these experiments demonstrate changes in performance as a result of primary task manipulation they still use a secondary task to measure changes in mental workload. Alongside brain activation there are a number of ways that the influence of mental workload on human performance can be measured without imposing a secondary task on drivers.

The most common technique is to measure performance from driver behaviour measures including speed, lane deviation, and headway. Higher workloads created by reduced road width and poor lane markings have led to changes in driving behaviours, such as a greater deviation in speed and lane position (de Waard et al., 1995; Horberry et al., 2006), thus demonstrating the sensitivity of driving behaviour measures to natural manipulations of mental workload. Such changes can be explained by theoretical models of behavioural adaption. For example the Task Capability Interface model (Fuller, 2000). This model poses that loss of control will occur when the demand of the driving task becomes greater than the capability of the driver. Task demand constantly varies based on road infrastructure and environmental factors. One of the most important determinants of task demand is speed, which is maintained by the driver. The model predicts that a change in speed will directly influence demand, and therefore perceived difficulty should be related to speed. A number of experiments have been conducted which provide support for this assumption. For example, Lewis-Evans and Rothengatter (2009) and Fuller et al. (2008) both reported that task difficulty ratings were highly correlated with drivers' speed choices.

Manipulations in experiments are often supported by subjective ratings which provide evidence of a successful manipulation of mental workload in the experimental design. For example, Horberry et al. (2006) used the NASA-TLX (Hart and Staveland, 1988) workload scale to confirm that changes in road width led to changes in mental demands. Subjective ratings are beneficial in research as drivers may alter their behaviour to suit task demands, and initial mental workload changes are not always evident in driver behaviours (Kaber et al., 2012), but may be reflected in subjective ratings (Cnossen et al., 2004). However, subjective ratings cannot be obtained simultaneously with the task without potentially influencing performance and therefore it may be beneficial to include other measures of mental workload alongside driver behaviour and subjective ratings.

Another technique is to measure changes using physiological measures of such as, skin conductance, respiration rate, and heart rate. Such physiological measures have shown changes as a result of mental workload manipulations (Kramer, 1990; Veltman and Gaillard, 1998). In a driving context, heart rate has been shown to increase incrementally with task demands, along with significant increases in respiration rate and skin conductance response, whereas changes were not detectable in driving performance until the highest workload level (Mehler et al., 2009). This suggests that physiological measures may be sensitive to mental workload changes before they are evident in driving behaviour. However, as with much of the research in the area, this experiment used an n-back task to manipulate workload during driving, as opposed to more ecologically valid primary task manipulations. Another physiological response and common technique used in driving research is eye tracking. As with other physiological measures, eye movements have been shown to be reflective of changes in mental workload in a driving context (Engström et al., 2005; Marquart et al., 2015). Research from simulated and on-road driving suggests that changes in mental workload results in changes in fixation duration and spread of search both when workload is manipulated by secondary tasks (Yang et al., 2012), and by natural changes in road type (Chapman and Underwood, 1998). For example, less complex rural roads produced longer fixation durations compared to more complex, urban roads that were associated with shorter fixation durations and a wider spread of search (Chapman and Underwood, 1998).

An important benefit of physiological measurements is that they can be recorded simultaneously with task performance and other measures, such as driving behaviour and subjective ratings, and are not normally under the conscious control of the driver. Despite this, it may be possible for people to control their heart and breathing rate, although this typically requires significant effort and concentration. A further limitation of physiological measurements is that they may also be sensitive to motion artefacts whilst driving and can be difficult to obtain complete, continuous, error-free readings for all participants (Goldberg and Wichansky, 2003).

It is important to understand whether natural manipulations of the primary driving task impact upon a driver's mental workload and whether such changes can be detected using measures that are recorded simultaneously and thus can be compared within the same experiment. It is also important to identify which measures, if any, are not sensitive to these changes. Such knowledge would promote the assessment of real time workload and may also be used to inform future developments of in-vehicles devices and partially autonomous driving systems. Based on the literature discussed two main aims are addressed in this experiment. The first is to examine whether changes in road types in a simulated driving environment are associated with changes in the mental workload experienced by the driver as measured using driving behaviour, subjective ratings, physiological responses and eye movements. The second aim is to explore whether changes seen in the aforementioned variables are also associated with changes in PFC activity as measured using fNIRS.