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Characterizing the Influence of Muscle Activity in fNIRS Brain Activation Measurements

Nils Volkening * **Anirudh Unni** ** **Birte Sofie Löffler** *
Sebastian Fudickar * **Jochem W. Rieger** ** **Andreas Hein** *

* *Department of Health Services Research, Division of Systems in Medical Engineering, Carl-von-Ossietzky University, Ammerländer, Heerstr. 140, 26111 Oldenburg, Germany (e-mail: Nils.Volkening@uni-oldenburg.de).*
** *Department of Psychology, Applied Neurocognitive Psychology, Carl-von-Ossietzky University, Küpkersweg 74, 26111 Oldenburg, Germany (e-mail: Anirudh.Unni@uni-oldenburg.de)*

Abstract: Driving is a complex and cognitively demanding task. It is essential to assess the cognitive state of the driver in order to design cognitive technical systems that can adapt to different driver cognitive states. Our research attempts to assess these states using functional Near Infrared Spectroscopy (fNIRS) by measuring brain activity in a virtual reality driving simulator. However, the fNIRS brain activation measurements could be influenced by muscle activity and we wanted to investigate this phenomenon. For this, we designed a paradigm with two conditions (listen, teeth clench) which show a significant contrast in the influence of muscle activity. We observed that the muscle hemodynamic response can show a higher magnitude of signal change compared to brain hemodynamic response. The muscle hemodynamic response showed an increase in deoxygenated hemoglobin (HbR) whereas the brain hemodynamic response showed a decrease in HbR. Moreover, the dynamics of the brain and muscle hemodynamic response differed. The brain response showed the same latency for oxygenated hemoglobin (HbO) and HbR while the muscle HbR response had a slower latency compared to HbO. We concluded that the fNIRS brain activation measurements could indeed be influenced by muscle activity. We were also able to determine some characteristics of the muscle hemodynamic response.

Keywords: driver cognitive states, fNIRS, brain and muscle activation, hemodynamic response, HbR, HbO

1. INTRODUCTION

1.1 Critical Systems Engineering for Socio - Technical Systems

The aim of Critical Systems Engineering for Socio–Technical Systems (CSE) is to integrate humans in the control loop of socio-technical systems. The subproject (The Car that Cares (CTC)) is responsible for the automotive domain. The overall objective of CTC is to develop processes, techniques and software tools to enable the development of socio-technical car systems, that continuously adapt to the internal context (e.g. health state of the driver, current tasks) and external context (e.g. weather, traffic) and offer situation-aware cooperative interaction with the driver of the car. This means that in CTC, the driver should become a part of the control loop so that assistive systems will receive feedback of different driver states e.g. cognitive, emotional and health states.

The degree of automation in vehicles is continuously increasing (Brookhuis et al., 2001). Many assistive systems have been introduced in the last decade that provide specific information to the driver and reduce their cognitive workload. For example, navigation systems provide important information to the driver, anti-lock braking systems stabilize the car in the event of a safety-critical situation and cruise control supports speed regulation (Freyman, 2004). However, the information channel between the driver and the assistive system is unidirectional as most of these systems receive little or no information regarding the driverfis state or goals. The integration of the human into the control loop of the driver assistive system is important in order to improve the performance of the assistive system based on the cognitive capabilities of a large human population. Our goal is to establish and optimize a continuous information flow between cognitive technical systems, as adaptive driver assistance and humans to adaptively support them in cognitively demanding driving situations (Unni et al., 2015). Somatophysiological sensors can be used to assess driver cognitive states. Healey and Picard (2005) analyzed data from somatophysiological sensors like electrocardiogram (ECG), electromyogram (EMG), galvanic skin response (GSR) and respiration rate to determine a driver’s relative stress level during real world driving tasks. Solovey et al. (2014) performed an extension study to discriminate three driving situations with increasing control demand above chance level using the above mentioned somatophysological sensors. However, it is not clear how specific somatophysiological recordings are for different cognitive demands. Neurophysiological measurements can also be used to assess cognitive workload levels (Kojima et al., 2005; Gateau et al., 2015; Tomioka et al., 2009). In our study, we used fNIRS as the neuroimaging modality to estimate these cognitive states. fNIRS has some advantages over other techniques like functional Magnetic Resonance Imaging (fMRI), electroencephalography (EEG) or magnetoencephalography (MEG). fNIRS measures both HbO and HbR concentrations and this extra dimension helps in motion

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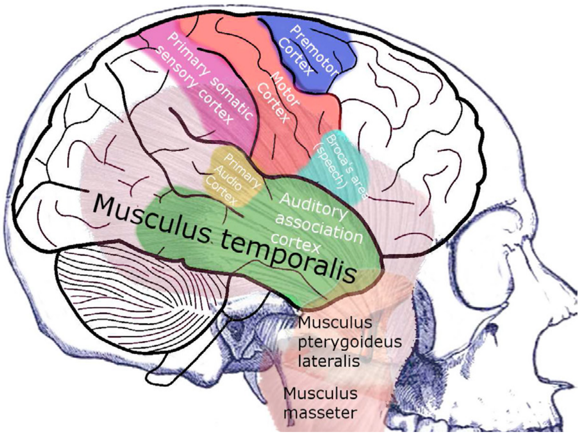

Fig. 1. Location of different muscles of mastication corresponding in relation to functional brain areas

artifact removal (Cui et al., 2010). It is unsuitable to measure brain activity in a naturalistic driving scenario using fMRI or MEG as they are immobile techniques. EEG has a worse spatial resolution compared to fNIRS which might not be good enough to discriminate driver cognitive states. However, the brain activation signals in fNIRS might be corrupted by the influence of muscle activity.

1.2 Hemodynamic Response in Brain Recordings and Potential Muscle Contribution to the fNIRS Signal

During neural activation, the hemodynamic response over the corresponding cortical area consists of a decrease of HbR accompanied by at least a two-fold increase in HbO. This hemodynamic response is delayed and peaks around 6 s to 10 s after neural activation is elicited by stimulus. However, fNIRS channels not only measure blood oxygenation changes caused by brain activation but changes elicited by any tissue that is in the light path between emitter and receiver (see Figure 2). The most common physiological artefacts in laboratory experiments which influence the fNIRS measurements are cardiac pulsations, respiratory signals, blood pressure (Meyer waves) oscillations which are present in the scalp and the underlying cerebral tissue (Obrig et al., 2000; Toronov et al., 2000; Franceschini et al., 2006; Cooper et al., 2012). While several studies characterized and developed methods to mitigate or remove these artifacts, little is known about the influence of muscle activity on continuous fNIRS brain activation measurements in naturalistic settings, where it is likely that drivers chew, drink, talk or clench their teeth. Muscles of mastication cover a large portion of the lateral skull (see Figure 1) and the light passes through the brain and some of these muscles as well which as a consequence, confounds signal variations due to muscle and brain activity. In addition to brain activation measurements, fNIRS has been used to characterize metabolism in skeletal muscles and Ferrari et al. (1997) showed that contrary to the brain hemodynamic response, both the HbR and HbO signals increase during muscle activity.

2. STATE OF THE ART

In the next sub-sections, we provide an overview of the principle and the physical properties of fNIRS, followed by related works for the estimation of cognitive states of the driver.

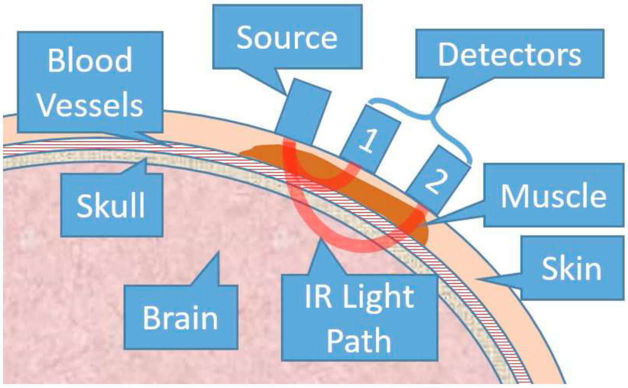

Fig. 2. Different light paths achieved by adjusting fNIRS channel (source-detector combination) distance. A long NIR light path sees influence of muscle and brain activities

2.1 Medical Background

FNIRS benefits from the fact that biological tissue and bones are nearly translucent for near infrared (NIR) light from 650 nm to 950 nm. The transmission path of NIR light in biological tissues can be described as a banana-shaped profile (Gratton et al., 1994; Ferrari and Quaresima, 2012). This property allows us to vary the depth of light path sampled at the sensor (see Figure 2). (McCormick et al., 1992; Villringer et al., 1993; Gratton et al., 1995; Gratton and Fabiani, 2010). Nevertheless, fNIRS is capable of measuring only the most superficial regions of the cerebral cortex because the light intensity becomes insufficient over distances beyond 5.5 cm (Parks, 2013). Most systems use at least two wavelengths (e.g. 760 nm and 850 nm), which represent the relative absorption coefficient of HbO and HbR respectively. The modified Beer-Lambert law is used to convert data from voltage to relative concentration changes of HbO and HbR respectively (Villringer et al., 1993; Sassaroli and Fantini, 2004).

2.2 Cognitive State of the Driver

A few research groups have been working on estimating driver cognitive states. (Unni et al., 2015) predicted cognitive workload during a naturalistic driving simulator experiment. There have been other fNIRS related studies in the transportation domain (Kojima et al., 2005; Dornhege et al., 2007; Tomioka et al., 2009; Tsunashima and Yanagisawa, 2009; Gateau et al., 2015; Pradhan et al., 2015). However, in all these studies, the participants were instructed not to speak during the experiment in order to avoid the influence of muscle activity (see Section 1.2). This is not the case in a real world scenario, where drivers perform multiple secondary tasks while driving e.g. speaking to other passengers or on their phone, chewing, etc.

In this study, we focus on brain activities from the temporal cortex that is known to be involved in auditory and speech processing (Binder et al., 1996). We focus in this brain area because processing auditory input is a very common secondary task in driving (e.g. radio, conversation, cell-phone usage, audible warning signal etc.). The presence of massive muscles in this area, e.g. musculus temporalis, as shown in Figure 1 causes the fNIRS brain activation measurements to be sensitive to muscle activity which we would like to characterize.