Transportation Research Part C 21 (2012) 122–133

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Towards a driver fatigue test based on the saccadic main sequence: A partial validation by subjective report data

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ARTICLE INFO

Article history:
Received 5 July 2010
Received in revised form 30 June 2011
Accepted 25 July 2011

Keywords:
Driving simulation
Eye movements
Mental workload
Cognitive load
Activation
Rest breaks

ABSTRACT

Developing a valid measurement of mental fatigue remains a big challenge and would be beneficial for various application areas, such as the improvement of road traffic safety. In the present study we examined influences of mental fatigue on the dynamics of saccadic eye movements. Based on previous findings, we propose that among amplitude and duration of saccades, the peak velocity of saccadic eye movements is particularly sensitive to changes in mental fatigue. Ten participants completed a fixation task before and after 2 h of driving in a virtual simulation environment as well as after a rest break of fifteen minutes. Driving and rest break were assumed to directly influence the level of mental fatigue and were evaluated using subjective ratings and eye movement indices. According to the subjective ratings, mental fatigue was highest after driving but decreased after the rest break. The peak velocity of saccadic eye movements decreased after driving while the duration of saccades increased, but no effects of the rest break were observed in the saccade parameters. We conclude that saccadic eye movement parameters—particularly the peak velocity—are sensitive indicators for mental fatigue. According to these findings, the peak velocity analysis represents a valid on-line measure for the detection of mental fatigue, providing the basis for the development of new vigilance screening tools to prevent accidents in several application domains.

1. Introduction

Developments in information technology have fundamentally changed working conditions from the second half of the twentieth century (Arvidsson et al., 2006). Many operations and procedures that were carried out by human operators are nowadays performed by machines and proceed in an automated way (Parasuraman and Riley, 1997). This automation has decreased the number of operators monitoring automated systems and the amount of physical resources requested from these operators. Moreover, cognitive processes, such as perception and attention, have become more important than "action" (Cacciabue, 2004; Boksem and Tops, 2008), leading to a kind of "fallacy of automation" in which the total resource demands are de facto not reduced but redistributed. Thus, today, operators perform cognitive tasks, such as planning,

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doi:10.1016/j.trc.2011.07.002

identifying or resolving problems, instead of manual tasks (Hollnagel, 1995). The continuous performance of highly demanding cognitive tasks produces mental fatigue (Thorndike, 1900), one of the effects deeply investigated in the human–machine interaction domain.

Fatigue is described as "undesirable changes in performance that could be linked to continued activity" (Bartlett, 1943) and is often considered to be analogous to muscle fatigue (Lal and Craig, 2001, for a recent review on this topic see Di Milia et al., 2011). However, mental fatigue is the "state of reduced mental alertness that impairs performance" (Grandjean, 1980) and "refers to the effects that people experience following and during the course of prolonged periods of demanding cognitive activity, requiring sustained mental efficiency" (Lorist et al., 2005). Acute as well as chronic forms of mental fatigue are a subset of human functional states (Leonova, 1998). According to Lal and Craig (2001), mental fatigue is one critical factor in modern technological society, being the major reason why most people become unable to avoid performance errors (Nilsson et al., 1997). For example, in Spain, mental fatigue is the fourth leading cause of fatal automobile crashes, following alcohol/drugs, meteorological conditions, and inexpertness in driving (RACE, 2009).

Although the theoretical and practical implications of mental fatigue are already known, measuring mental fatigue—especially in complex, dynamic tasks—is still challenging (Shen et al., 2008). Recent studies investigated mental fatigue using behavioural measures, such as eye movements (Stone et al., 2003; Schleicher et al., 2008), psychophysics, fMRI and EEG (Wijesuriya et al., 2007; Cook et al., 2007; Smiley, 2007). Due to the difficult and complex set up, the imaging measures are less appropriate for the use in applied scenarios outside the lab (Di Stasi et al., in press). Therefore, ecological non-intrusive methods for assessing driver fatigue are needed.

Here, we suggest a new non-intrusive method for assessing mental fatigue that extends earlier attempts (Schleicher et al., 2008; Hirvonen et al., 2010). Our proposal is based on the idea that particular stages of brain activity reflect the driver's alertness. In vertebrate embryonic development, the eyes originate as outgrowths of the brain and are therefore considered part of the central nervous system (Wilson and O'Donnell, 1988; Hain, 1992). Accordingly, the analysis of gaze parameters should provide optimal indices of alertness and an easy way of quantifying and tracking mental fatigue (Morad et al., 2009). Some eye parameters (for example, pupillary dilation or the speed of saccadic movement) are not under voluntary control (Leigh and Zee, 1999) and are therefore assumed to be directly sensitive to the effects of fatigue, as they cannot be affected by the driver's motivational state (Rowland et al., 2005).

Eye tracking devices quantify three potential sources of information about the driver's mental state: eye movements, blink rate, and pupil size (Wickens and Hollands, 2000). Blink rate and pupil size have often been analyzed while driving (e.g. Recarte and Nunes, 2000; Nunes and Recarte, 2002; Benedetto et al., 2011) and are known to be affected by fatigue (e.g. Stern et al., 1994); however, these parameters are of limited value for detecting fatigue onset. Increased blink rate due to increased fatigue means that the eyes are closed more often, resulting in a greater number of periods of visual information loss and therefore the likelihood for performance error increases. According to Velichkovsky et al. (2002a), a normal blink rate (without indications of fatigue) already results in being 'blind' for up to 4% of the time. For an average workday of 8 h, this equates to a loss of visual information of approximately 20 min. While the majority of errors is caused by inattention, increased blink rate and blink duration, (Morris and Miller, 1996), measures are required that are not based on the rate and duration of having the eyes closed. Detecting indications of fatigue even before it is expressed in the blink behaviour minimizes information blindness and could therefore reduce performance error. Regarding the pupil size, there are various influencing factors besides fatigue such as emotion and ambient lighting (Beatty and Lucero-Wagoner, 2000) that play a role, making it difficult to attribute pupil size changes to individual factors. The approach we present here focuses particularly on the dynamics of saccades as a reliable indicator of fatigue. In doing so we attempt to find indications of fatigue even before it is manifested in the blink rate.

1.1. Main sequence as mental fatigue index

For visual information processing it is important that high visual acuity is limited to the small foveal area. Hence, eye movements are essential for exploring different parts of a scene. These fast ballistic movements—saccades—are performed on average about three times a second. Saccades vary in amplitude, duration, and (peak) velocity [PV] (Dodge and Cline, 1901; Dodge, 1917). The relationship between these parameters has been called the 'main sequence' to describe the fact that PV and duration increase systematically with the amplitude (Bahill et al., 1975). However, PV is "independent" of the duration since there is no mathematical function that links both parameters (Becker, 1989).

As a result of their investigation of fatigue and saccadic eye movements, Bahill et al. (1975) discussed the importance of using saccadic eye movements as an indicator of general psychological states when performing various tasks, even in the field of human factors engineering. However, after more than 30 years, this suggestion has received only little attention (Parasuraman and Rizzo, 2007; Schleicher et al., 2008). So far it has been shown that the complexity of tasks as well as the presence of a secondary task influences saccadic velocity (e.g. Galley, 1998). In visual tasks, it has been demonstrated that saccadic velocity is influenced by the degree of mental activation (App and Debus, 1998), alertness (Thomas and Russo, 2007), natural fluctuation of vigilance (Fafrowicz et al., 1995), sleep deprivation (Zils et al., 2005), drug-induced sedation (Grace et al., 2010), mental workload (Di Stasi et al., 2010a,b, 2011a,b), and fatigue (e.g. Schmidt et al., 1979; Morad, et al., 2009; Hirvonen et al., 2010). In most of these previous works, the relationship between performance indicators and saccadic behaviour has been studied by designing experiments in which oculomotor performance is dissociated from the natural role of the saccades, which rapidly bring perceptual information to the fovea (Montagnini and Chelazzi, 2005). Pre-