LEANDRO LUIGI DI STASI

MENTAL WORKLOAD IN HMI

AN APPROXIMATION TO A MULTIDIMENSIONAL METHODOLOGY FOR ONLINE MEASUREMENT OF MENTAL WORKLOAD IN THE REALM OF ROAD DRIVING.

TESIS DOCTORAL

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Departamento de Psicología Experimental y Fisiología del Comportamiento**.**

CARGA MENTAL EN HMI (INTERACCIÓN HOMBRE-MÁQUINA):

APROXIMACIÓN A UNA METODOLOGÍA MULTIMODAL DE MEDICIÓN ON-LINE DE LA CARGA MENTAL EN EL ÁMBITO DE LA CONDUCCIÓN VIAL

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Tesis Doctoral presentada por ***Don Leandro Luigi Di Stasi*** en el Departamento de *Psicología Experimental y Fisiología del Comportamiento* para aspirar al grado de Doctor en Psicología, en el programa de doctorado de *Psicología Experimental y* Neurociencias *del Comportamiento*, de la Universidad de Granada.

La tesis ha sido realizada bajo la dirección de los profesores ***José Juan Cañas Delgado, Andrés Catena Martínez y Thierry Baccino***, quiénes avalan la calidad de la misma, así como la formación del doctorando para aspirar al grado de doctor.

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To my Family and to You with
Вера, надежда, любовь

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PREFACIO (in Spanish)

LA CARGA MENTAL

Mas de treintas años después de la formalización del constructo de carga mental [CM] (Welford, 1977; Leplat y Welford, 1978; Moray, 1979) y de miles de investigaciones sobre el tema, la carga mental sigue siendo uno de las grandes limitaciones en el desarrollo de la *"information civilatiation"*. El constructo ha sido definido como "la acción dedicada a mantener una actividad en un nivel de atención focal" (Kahneman, 1973), como el coste (cognitivo) de realizar una tarea (Wickens 1984; 2002; 2008), o mas genéricamente "(…) la combinación de estados mentales o conjunto de estados que median el desempeño perceptivo, cognitivo y motor de la persona" (trad. de Parasuraman y Caggiano, 2002, p.17). La CM, como indica su definición, no supone una dificultad en sí misma, sino que conforma el estado de activación cognitiva necesaria para el desempeño de la tarea. El problema deriva de la situación de desequilibrio entre las demandas de las tareas y las capacidades del individuo, tanto por exceso como por defecto. Es decir, tomaremos un problema de CM como aquél en el cual el individuo no pone en funcionamiento las capacidades cognitivas requeridas para la ejecución de la tarea, sea porque pone en funcionamiento más recursos de los demandados por la actividad (subcarga mental) o porque pone en funcionamiento menos recursos de los demandados por la actividad (sobrecarga mental). Éste último suele ser el concepto al que se hace referencia cuando coloquialmente se habla de CM. Esta situación de desequilibrio produce la reducción de la capacidad del individuo en ese momento, que suele traducirse en una disminución de la atención y de la motivación, así como de un pensamiento ralentizado. Esto conlleva tanto bajo rendimiento y reducción en la actividad como un aumento significativo en el número de errores cometidos. Si este estado se mantiene en el tiempo, las consecuencias para la salud abarcan desde la inestabilidad emocional (irritabilidad, ansiedad, estados depresivos, etc.), alteraciones del sueño y astenia hasta alteraciones psicosomáticas (mareos, alteraciones digestivas, cardíacas...). Tanto el aumento de errores que conlleva la CM como las graves consecuencias a nivel individual, grupal y social, cuando se convierte en un estado crónico, han marcado la intervención en CM como una demanda social prioritaria.

Existen por los menos cuatro modos para entender/explicar la carga mental: 1) los recursos exigidos por la tarea: si la dificultad aumenta, se deduce un aumento de la carga mental. 2) el nivel de prestación que el operador alcanza: si los errores aumentan, o disminuye la precisión del control ejercido, se deduce un aumento de la carga mental. 3) el esfuerzo ejercido por el operador al ejecutar la tarea: la carga mental reflejaría en este caso la respuesta del operador, más que la carga impuesta por la tarea. 4) la percepción del operador: si un operador se siente bajo esfuerzo o sobrecargado, la carga mental puede aumentar (aunque las demandas de la tarea no cambien). Este tipo de clasificación nos puede ayudar a comprender la complejidad del constructo, pero en la realidad la misma naturaleza del fenómeno es una conjunción de todos estos elementos. Actualmente, existe acuerdo general en admitir que la CM es multidimensional y que, por lo tanto, está determinada por diferentes factores o dimensiones (O'Donnell y Eggemeier, 1986). Esta multidimensionalidad de la CM implica el interés de múltiples disciplinas, dando lugar a la aparición de numerosos estudios y publicaciones sobre este tema (Hancock y Desmond, 2001). La capacidad de medir la carga de trabajo mental correctamente y estimar continuamente el esfuerzo del operador está estrechamente relacionada a la medición de la seguridad industrial (Gould et al., 2009), la mejora de la usabilidad de las interfaces (Casner, 2009), y el diseño de estrategias apropiadas y adaptables para la automatización (Jou et al., 2009; Cacciabue y Carsten, 2010).

EL CONSTRUCTO DE CARGA MENTAL EN LA SOCIEDAD DE LA INFORMACION

La importancia de la CM en el ejercicio de las tareas laborales es tal que la demanda social ha conllevado su reflejo legislativo en casi todos los países, reconociendo que afecta a la salud mental y física del trabajador. En nuestro país, ha sido la Ley de Prevención de Riesgos Laborales a través del Real Decreto 488/ 1997 de Pantallas de Visualización de Datos quien se ha hecho eco de estas consecuencias, considerando la Carga Mental una fuente muy importante de riesgos en los ambientes de trabajo frente a la que el empresario debe actuar. Durante la segunda mitad del siglo veinte, el desarrollo de la “tecnología de información” ha cambiado mucho las condiciones del trabajador (Arvidsson et al., 2006). Hoy día, como consecuencia de la automatización masiva, es habitual que los sistemas desempeñen tareas que antes eran realizada por una persona. Esta idea se vio clara desde el principio de la automatización del puesto de trabajo (Parasuraman y Riley, 1977). El resultado de la automatización creciente en los lugares de trabajo (desde los de despacho a la conducción de camiones) es la reducción tanto del número de operadores implicados en el control de los sistemas automatizados como de la cantidad de recursos físicos solicitados a los mismos. Otro resultado importante es que los procesos cognitivos, como percepción y atención, se han hecho más importantes que "la acción" (Cacciabue, 2004; Boksem y Tops, 2008). Podríamos llamar a este efecto “el error de la automatización”, para indicar que las demandas de recursos en el lugar de trabajo no se han reducido, sino al contrario redistribuido, lo que significa que el operador realiza mas tareas cognitivas, como diagnosticar, planear o resolver problemas, que tareas manuales (Hollnagel, 1995). La evaluación de la CM en la interacción hombre-máquina [HMI] es un tema de gran interés social y constituye una de las áreas centrales en el campo de la Ergonomía Cognitiva aplicada, que trata de cubrir los objetivos esenciales de búsqueda de confort, satisfacción, eficacia y seguridad (Cañas, 2004).

EL PROYECTO DE TESIS

La presente tesis se ha planteado el desarrollo de una metodología multimodal adecuada para evaluar el estado psicofisiológico del conductor (nivel de atención y estado de fatiga) en el campo específico de HMI en diferentes condiciones de conducción, enfatizando el uso de medidas psicofisiologicas, relacionadas con los movimientos oculares. Después de una extensa revisión de los índices usados actualmente para la medición de la CM (Capitulo I, Di Stasi et al., submitted b), se ha planteado una serie experimental (Capítulos, II, III, IV, V, VI -Di Stasi et al. 2009; Di Stasi et al., 2010 d, c; Di Stasi submitted et al., a, d) para validar la sensibilidad de un parámetro concreto del movimiento saccadico “Saccadic Peak Velocity” [PV], como medida alternativa para la monitorización del estado cognitivo del conductor. Con el fin de comprobar nuestras hipótesis y antes de aplicar los resultados a un contexto real, se han empleado diferentes tipos de simuladores/tareas, evaluando tanto mediante medidas on-line de desempeño e índices psicofisiológicos, como de informes verbales y valoraciones subjetivas (cuestionarios). En el sector de automoción, los resultados de este proyecto (capitulo VII, Di Stasi et al., submitted c) se podrán implementar en los futuros sistemas tecnológicos de ayuda a la conducción (Di Stasi et al., 2010 b; Di Stasi et al., submitted b) y en los programas de entrenamiento (Di Stasi et al., 2010 a).

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CHAPTER I. INTRODUCTION

Saccadic Peak velocity: The necessity of an on-line attentional index

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ABSTRACT

Automation research has identified the need to monitor driver functional states in real time as a basis for determining the most appropriate type and level of automated assistance for her/him while driving. For this reason, the development of a methodology that is able to detect on-line driver attentional resource variations could represent a good starting point to solve this critical issue. In this doctoral thesis we present an experimental series that demonstrates the validity and sensitivity of a specific eye movement index; i.e. saccadic peak velocity (PV), that is able to detect variations in mental state (workload/fatigue) while doing complex and ecological tasks. PV was tested in different experimental contexts, as well as air traffic control simulated tasks and driving simulator sessions. Our research is relevant to a variety of domains, ranging from air traffic control towers to logistics services company. For example, using real-time main sequence measures, neuroergonomists could better evaluate when an operator's attentional state is changing (mental under/overload or fatigue), helping in the design of systems able to allocate tasks in a dynamic way between the operator and the machine. The current work could be a starting point for further research on understanding how variations in cognitive processing and mental workload can be used to build a model to manage the dynamic allocation of tasks between human operators and support systems. We are now trying to validate these results, applying the same methodology during complex interactions task, to develop an assistance system able to reduce the risk of accidents by assessing operators' mental workloads and attentional states in hazardous conditions.

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1. INTRODUCTION

In a technological information society, changes in attentional state can have significant impact on operator performance, possibly leading to delays in information processing or even causing operators to ignore incoming information (Ryu & Myung, 2005). Consequently, there is a need to monitor operator functional states in real time to determine the type and level of automated assistance most appropriate in helping operators to complete tasks (Langan-Fox et al., 2009). Development of a method able to detect operator attentional states in real time during interactions with complex and dynamic systems could be a good starting point for this critical issue.

In Cognitive Psychology and Cognitive Ergonomics, the idea that mental activity can be envisioned in an "energetic" perspective in which quantities of activity can be measured, can be found in the first pioneer works of the two disciplines, together with studies on factors that can increase or decrease mind activity levels (Cañas, 2004). From both a purely theoretical point of view (and consequently in the relative framework of basic investigation) as well as in real work context application studies (for increasing or at least preserving comfort of operators, developing high quality instrumentation or ameliorating interactions with technologies), mental activity has been regarded for many years as a set of processes for which quantitative measures could be determined. Thus, the notion of "load" is one of the core issues in mental activity investigation and modelling. According to this dynamic conception of mental activity, mental workload has progressively been given more importance, especially in ergonomic studies of operator performance in safety-critical contexts, such as industrial plants (e.g., processing industries and nuclear power plants) and transportation systems.

The existent literature on workload topics is very wide, and a number of reviews on the concept have existed for years. As with all constructs that are not directly observable, there are several definitions of mental workload. A common trait of almost all definitions is the presence of a task (or, more generally, a situation) that requires an effort (mental or physical) that a subject has to sustain, according to his/her possibilities. The quantity of effort that can be directed to the task depends on many factors related to the task as well as to the subject him/herself. One of the definitions that more explicitly covers the aforementioned aspects is that provided by Parasuraman and Caggiano (2002, p.17): "Mental workload refers to a composite brain state or set of states that mediates human performance of perceptual, cognitive, and motor tasks". Moreover, mental workload can be driven exogenously (or "bottom-up") by environmental sources, namely, by task load, as well as endogenously (or “top-down”) by voluntary mental effort. In this definition it is clear that the connection between mental activity and brain activity, for which many measurement techniques have been developed throughout the last decades, de facto, mind is a function of brain.

2. MEASURING ATTENTIONAL STATE IN REAL WORK CONTEXTS

Currently, three sets of methods are most prevalently used to evaluate mental workload: (1) subjective reports of perceived effort by the operator; (2) methods based on the performance level reached by the operator in a secondary task; and (3) psychophysiological indices that reflect the cognitive state of the operator.

Primarily, mental workload is measured using subjective tests. A variety of tests and questionnaires have been developed to quantify this subjective rating. Some of these instruments use subscales to provide separate indices of the different dimensions of mental workload. They have the advantage of being relatively easy to administer and to interpret, and they do not require extensive training or expensive equipment. However, although these subjective techniques are popular, there are several methodological problems associated with their use (Tsang & Velazquez 1996). First, they tend to be specific to the situation and frequently fail to be influenced by adaptability, learning, experience, innate ability, and changes in the emotional state of the person performing a task. Second, the subjective measures generally perform poorly when there is little variation in mental workload. And third, they do not assess evolution over time. Furthermore, correlations with performance measures are not perfect (Yeh & Wickens, 1988, Horrey et al., 2009). These are problems common to a variety of research fields in cognitive ergonomics. The main problem with subjective techniques, however, is their off-line nature, which often make them unpractical or intrusive, as when for instance control operators are asked to fill in mental workload questionnaires off-duty, during rest breaks or even worse, at lunch time. Indeed, intrusiveness can convert subjective questionnaires into requiring further effort.

Performance based techniques for assessing mental workload are based on measuring response times and performance accuracy while the subject performs a task. Their validity has been supported by extensive investigations (Brünken et al., 2003 or Madrid et al., 2009). Their most important advantage is that they provide data that are less influenced by personal and confounding factors, and they are objectively verifiable by outside observers. However, they are demanding, tend to be more specialized, and require expensive equipment and extensive training of the person administering them (Christodoulou, 2005). Furthermore, in most situations they cannot detect small variations in mental workload, they do not always or necessarily evaluate mental workload directly, and they can be insensitive to variations in the difficulty of the task. In conditions where multiple tasks must be undertaken, the operator's sustained attention may get increasingly involved, making the main task performance more difficult.

Because of the problems associated with subjective and performance measures, researchers and practitioners have turned their attention to the promising area of psychophysiological indices. In recent years, there have been numerous reviews of the application of psychophysiological techniques to ergonomics and, in particular, to the area of mental workload (for examples, see Kramer, 1991; Wilson & Eggemeier, 1991; Gevins et al., 1995). Several indices of mental workload and performance have been developed, based on studies conducted in the laboratory and in simulation and operational environments. The more important indices that have been employed in the assessment of mental workload in applied settings are respiration, heart rate, electrodermal activity, some components of electroencephalic activity, and some parameters related to eye activities (Kramer & Weber, 2000).

In the last twenty years, the commonly used indices of mental workload have been heart rate and respiration (Wientjes, 1992; Jorna, 1992). These have been used in a variety of experimental settings (for a review, see Kramer & Weber, 2000), from the early experiment of Gemelli (1917) involving real-flight performance of military pilots to the most recent work of Pattyn et al. (2008) in a laboratory context or in open field (Dey & Mann; 2010). However, the use of heart rate has been often criticized (e.g., Kahneman 1973) and respiratory measurements are still rather uncommon in applied research. Furthermore, a number of technical problems associated with acquiring these two indices make it impossible to apply them in working environments. Two common sources of artifacts for these indices in applied settings come from speaking and muscle activity (Jorna, 1992; Porges & Byrne; 1992, Wientjes, 1992). It is impossible for an air-traffic controller or for refinery operators, for example, to be assessed without moving or speaking. Furthermore, as happens with most common physiological measures, cardiorespiratory indices fail to produce reliable results because they lack specificity and have hyper-hypo sensitivity (Roscoe, 1992). These problems are important because in applied contexts it is impossible to define stable task loads and it is therefore impossible to define clear causal relations (Mulder, 1992).

Skin conductance and other electrodermal measurements have been extensively used to study variations in cognitive demand during a task (e.g., Naccache et al., 2005; Gould et al., 2009; for more specific information about this measure, see Dawson et al., 2007). However, even if there are many advantages in using this technique, including low-weight devices and relative lack of intrusiveness, an important problem makes the application of this technique outside of a laboratory context impossible. Indeed, as happens when measuring heart rate and respiration, the body creates noise that interferes with skin activity recording (Min et al., 2002; Yoshino et al., 2007).

Cerebral activity measurements, such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), provide an opportunity for a more direct assessment of mental workload (Ryu & Myung, 2005). Several studies have shown that the fMRI signal in regions that are sensitive for workload (the prefrontal and parietal cortices) increases as the demands imposed on working memory increase (e.g., Rypma et al., 1999; Jansma et al., 2000). However, EEG and fMRI are difficult to monitor outside specialized laboratory environments. Functional neuroimaging techniques require massive machinery, large multidisciplinary teams of technicians, and in some cases complete immobilization of the subject (Gevins & Smith, 2003). This makes assessment in industrial operations close to impossible.

Furthermore, despite the promising results from some studies using psychophysiological indices, the types of tasks studied in research settings, such as performing verbal calculations, observing photographs, or troubleshooting, make it difficult to extend the findings to real-life ergonomic situations. Also, these psychophysiological indices have been obtained in well-controlled experimental laboratory settings that are very different from the natural settings in which cognitive ergonomists and human factors professionals hope to assess. For example, Murata (2005) recently showed that EEG signals could be analyzed to discriminate cognitive task loads, with increasing cognitive task load seeming to delay the time at which the central nervous system works most actively (the appearance time of the θ, α, and β frequency bands increased as task difficulty increased). However, this author used an experimental task in which participants had to simply indicate whether a current stimulus matched a stimulus presented on a previous trial.

Therefore, we need to look for an alternative method to evaluate mental workload, one that can be used in more ecological and less artificial conditions and that avoids the problems mentioned above. In this paper, we present some experimental data in favour of such an alternative method, using a parameter of eye movement activity known as saccadic peak velocity (PV). Our proposal is based on the assumption that brain activity offers the best estimation of mental workload, and since the eye is, embryologically, an extension of the brain (Hoar, 1982; Wilson & O'Donnell, 1988), some eye activity parameter may be a suitable index. We propose that videooculography may be an optimal solution because it supplies a continuous, reliable measurement that can monitor unexpected and continuous changes in mental workload.

3. OCULOMOTOR INDICES

Eye tracking has been a tool in Human Factors since the 1950s, when for instance eye movements of pilots flying landing approaches were studied. Ocular movements are often studied to understand perceptual-cognitive processes and strategies mediating performance in complex tasks (Parasuraman & Rizzo, 2007).

In recent years, thanks to technological progress (which reduced intrusiveness), eye tracking methods for mental load assessment have received increasing attention. The basic assumption is that brain activity offers the best estimation of mental workload and since the eye is an extension of the brain (Wilson & O'Donnell, 1988) ocular indexes can reflect changes in mental activity related to the task being performed.

Eye tracking introduces three new potential sources of information about user mental workload: blink rate, pupil size, and parameters related to eye dynamics. Moreover, gaze behaviour (durations and directions) have been traditionally studied. Pupil diameter and blink rate are the most popular eye-movement indices for mapping mental workload (Wickens & Hollands, 2000; Ahlstrom & Friedman-Berg, 2006; Schleicher et al., 2008).

The positive relationship between cognition and pupil dilation has been well established by psychological research (Marshall, 2007), and some researchers have also found a link between eye blinks and cognition (e.g., Ryu & Myung, 2005). However, some problems make these indices difficult to use with dynamic and complex tasks. For example, using blink rate as an indicator of mental workload is problematic because with the closed eye a lot of information is lost. According to Velichkovsky et al. (2002), if we consider only the number of blinks that are made in a minute, a person is 'blind' for up to 4% of the time; this means that during a complex task, such as air traffic control, information is lost for approximately 15 minutes (considering duty times for an air traffic controller in a busy daytime) (Gander, 2001). Considering that the majority of errors are caused by inattention and that blink durations and rate increase as functions of time-on-task [TOT] and fatigue (Morris & Miller, 1996), it should be recognized that measures that avoid information blindness is needed. We need to detect dangerous levels of fatigue before inattention or errors happen. For this reason, among others, most researchers have directed their attention to pupil diameter.

Several researchers have demonstrated a strong correlation between variations in pupil amplitude and the amount of cognitive resources used to perform a task (Kahneman & Beatty, 1966; Beatty & Lucero-Wagoner, 2000; Le Duc et al., 2005; Jainta & Baccino, 2010). However, recent data cast doubts on the validity of this index for studying human–machine interactions. Schultheis and Jameson (2004) measured pupil diameter while people read texts of different difficulty, to evaluate the validity of this index in adaptive hypertext systems. They found no significant differences in pupil diameter when text difficulty was changing. More recently, Conati and Merten (2007) explored the validity of pupil diameter for online assessment of user meta-cognitive behaviour during exploration based learning. They also found that pupil size was not a reliable predictor of mental workload.

From the early years of ergonomic research, gaze measures, as gaze duration or gaze direction, were often used to assess mental states of operators (for more details see Kramer & Parasuraman, 2007). As recent studies have confirmed it is known that visual scanning behaviour is sensitive to variations in MW. For example, Di Stasi et al. (submitted b) have reported an experimental study in which participants interacted with an e-commerce website in two searching tasks (goal-oriented shopping and experiential shopping), each demanding different amounts of cognitive resources. In this study, results showed visual scanning behaviour coincided with subjective test scores and performance data in showing a higher information processing load in goal-oriented shopping. We may assume that experiential shopping is easier than goal-oriented shopping. Therefore, in experiential shopping there is an optimal level of arousal and, consequently, better planning of the visual behaviour. On the other hand, in goal-oriented shopping the level of arousal is higher due to the task aim: to buy a product taking care of specific features (under the same temporal constraint). Even if the above cited investigation confirmed that MW affects eye fixation variability, the relation between attentional state and fixation duration is still not clear. Some authors have shown an increase in fixation duration under high MW conditions (e.g. Bellenkes & Wickens, 1997); others have found the opposite result; i.e., that more frequent fixations reflect additional effort when processing visual information load (Camilli et al., 2008).

Nevertheless, eye movement parameters related to saccadic movement dynamics have received less attention from researchers investigating mental workload. It could be the case that some parameters related to saccadic movements are influenced by mental workload and that such a parameter could be a good alternative to blinking rate or pupil size for measuring mental workload in natural settings.

3.1. THE MAIN SEQUENCE

The relationships between duration and magnitude and between peak velocity and magnitude over a wide range of human saccades are indicated as Main Sequence, and they have been used to interrelate several hypotheses concerning the generation and control of saccades (Bahill et al., 1975). During the first 20 ms (more or less) of a saccadic movement, velocity tends to be the same regardless of target position. However, for the next 80 ms (or more), target position affects saccadic acceleration, which increases up to a point before velocity declines slightly and is maintained until reaching the target. Peak velocity is the point at which acceleration turns to negative, namely the point at which maximum saccade velocity is reached. Peak velocity measurement does not depend on thresholds used to define start and end points of a saccade, while saccade duration does (Becker, 1989). Saccadic parameters have been used as markers of task performance (Galley, 1998). Moreover, empirical research has also shown relations between saccadic dynamics and activation state (Galley, 1989; 1993; Galley & Andrès, 1996; Schleicher et al., 2008). While saccadic amplitude and saccade latency can be used as indicators of performance, saccadic speed is related to the activation state in visual performance tasks (App & Debus, 1998). It is therefore reasonable to hypothesize that, in visual tasks of long length (e.g. monitoring of devices), saccadic speed could change according to the state of activation. However, as App and Debus (1998) have suggested, saccadic (mean) velocity has not been used as an indicator of mental state because it is strongly dependent on saccadic amplitude and orbit direction, two variables that in real contexts are usually uncontrolled. For this reason, PV, which is not linked a priori by a mathematical formula to saccadic amplitude or duration, could represent a possible sensitive index of task complexity.

3.2. SACCADIC VELOCITY: THE ORIGINAL WORKS

During the first decade of the 20th century, Dodge and Cline (1901) and Dodge (1917), using a photographic technique of corneal reflexion recording, studied the dynamics of saccadic movements. The authors noted that saccade generation was influenced by the organism's state of "arousal" and that it may be impaired (among all, reduction in angle velocity) by mental fatigue.

In the 1970s, Bahill and Stark (1975) concluded their work discussing the great potential utility of using saccadic eye movement indices as indicators of general psychological state while performing real tasks; notwithstanding, in the field of neuroergonomics, this suggestion still needs to be considered (Parasuraman & Rizzo, 2007; Schleicher et al., 2008).

Even if some authors studied the relationship between performance indicators and activation indicators, such as saccadic behaviour (for more details see Galley, 1998), researchers have generally designed experiments such that oculomotor performance is dissociated from the natural role of the saccades; i.e. to make crucial perceptual information rapidly available for high resolution (Montagnini & Chelazzi, 2005). For example, in visually complex and dynamic tasks, such as driving a car, saccadic eye movements play an important role, namely to direct the foveal gaze to the area of interest, which has direct consequences for task performance.

To the best of our knowledge, only a few researchers have investigated the saccadic dynamics in complex tasks such as driving simulations (Galley, 1993; Schleicher et al., 2008) or in real road environments (Galley & Andrès, 1996).

The aim of the original work of Galley (1993) was to test electro-oculograms [EOG] as a sensitive tool for measuring online driver gaze behaviour. Gaze and blinking behaviour were reordered during three different simulated conditions, differing on the "secondary task" that participants had to perform. The experimental design "forced" the participant's gaze behaviour to look for information present in different positions on the dashboard of the simulator (for example, several digital displays or lateral mirrors). The results, considering the secondary task, showed that blink rate went up when the concurrent task finished and that saccadic velocity decreased according to mental fatigue (time-on-task). The author concluded that blinking behaviour could be a good indicator of visual behaviour interruption costs (derived by performance of the secondary task) and that saccadic velocity could represent a sensitive index of driver (de)activation. Even if this study represented the first great approximation of saccadic behaviour study in complex and dynamic conditions, the use of the EOG, induced to "force" participant gaze behaviour, created unnatural driver interaction (by defining several distant targets from the projected road simulation).

Some years later the investigation of Galley and Andrès (1996) overcame the caveats of Galley's work. Authors applied the same methodology (now including fixation durations among variables) to study the effect of long-term driving (drowsiness) on motorways in natural driving conditions (without forcing any secondary task). Fifteen participants drove at least 6 hours per day during 5 days. In this study, authors used the saccadic parameters as indicators of changing information processing, manipulating three main factors: the road environment (city vs. motorway); tiredness (time-on-task: five to one hour blocks) and consumption of alcohol (0 mg vs. <0.5 mg). Authors found effects with city vs. motorway and with vigilance (time-on-task and alcohol intake). Regarding saccadic velocity, a clear increase of mean values reflected an increase of information processing while driving in the city, and only moderated decrease of it, due to vigilance changing (reduction) in other cases.

Finally, Schleicher et al. (2008) examined the changes in several oculomotor variables (including main sequence parameters and blinking behaviour) as a function of increasing sleepiness in simulated traffic situations. Also, in this experiment, the EOG was used as a psychophysiological measuring instrument. Participants had to drive for about two hours in a monotonous road circuit, without any secondary task. The results showed that blinking behaviour (blink duration, delay of lid reopening, blink interval and standardised lid closure speed) was the best indicator of subjective as well as objective sleepiness. Among saccadic dynamics parameters, mean saccadic duration showed only modest changes with increasing sleepiness.

These studies are quite similar. Without considering the experimental context and psychophysiological measuring instrument (EOG), researchers used a standardization procedure Schleicher et al. (2008) to eliminate the influence of changing amplitudes on saccadic duration and velocity, and both considered the saccadic mean velocity as a third element of the main sequence relation, showing a general decrease of mean saccadic velocity as driver fatigue (or deactivation) increases

4. DOCTORAL THESIS OVERVIEW

In this doctoral thesis are discussed five experiments aimed to test the validity and sensitivity of the saccadic main sequence, and in particular PV as an attentional state index, in several experimental settings (from simulated air traffic control tasks to driving simulator sessions). If compared to Galley's works (see above) the reader will find three main differences: 1) the psychophysiological measuring instrument (in this case video-oculography at 500 Hz of sample rating - Eye Link systems), 2) the procedure of data analysis. In this doctoral thesis was used the saccadic-bin analysis (i.e. the analysis of PV and saccadic duration as a function of saccade length, in order to control the influence of saccadic magnitude). 3) PV instead of mean saccadic velocity was analyzed.

Following the recent tendency in applied ergonomics to use a combination of performance, subjective, and psychophysiological measures to assess user' MW (Brookhuis et al., 2008), in all presented experiments, the variation of main sequence parameters (saccadic amplitude, duration and PV), was evaluated multidimensionally. Whereas subjective measures offer us information about user' perceptions of the conditions of work, performance-based and psychophysiological measures provide information about the objective conditions of the tasks' requirements for specific resources (Hokey, 1997). Furthermore using psychophysiological measures allows continuous evaluation of mental state in real time (Miyake et al., 2009; Trimmel al., 2009).

For the first approximation to the problem (**Chapter II,** Di Stasi et al., 2009), eye-activity parameters was included in the methodology used to study the relationship between risky driving behaviour and MW. The results described in this chapter showed that between high/low risk rider groups, the high-risk group had shorter saccade duration and a higher saccadic PV than the low-risk group. On the Mental Workload Test [MWT] the high-risk group scored significantly higher on both perceptual/central and answer demand. Furthermore, PV showed several significant correlations with MWT dimensions. The negative correlations of PV and subjective scales of MW suggested that, given a high level of risk proneness, lower PV was associated with a higher level of subjective workload. However there are some caveats to this work. Due to the complexity of the simulated scenarios, the authors analyzed normalized (by saccade number) PV values, considering the difference between the test session and training session (baseline), but without applying the bin-analysis (analyzing PV as a function of saccade length), necessary to control for the influence of amplitude on PV.

Similar results are presented in **Chapter III** (Di Stasi et al., 2010 c) In an experiment that simulated multitasking performance in an ATC setting, it was studied the relation between the main sequence parameters and task load. The created tasks demanded different perceptual and central processing resources, as well as response resources. Three different levels of task complexity (low, medium and high) were created by manipulating the number of simultaneous tasks to be carried out. The number of simultaneous tasks was assumed to affect information processing load (Wickens, 2002). Low task complexity was defined as a monitoring/decision task. Medium task complexity involved a low-complexity task and a digit code task. In the high task complexity condition, the task was a combination of low- and medium-complexity tasks and a mathematical operation (paper and pencil) secondary task. All subjects started with low task complexity and proceeded through the same order. Results obtained from the subjective ratings Mental Workload Test [MWT], and behavioural measures (number of errors and delayed answers) confirmed that MW levels varied according to task demand. These different levels of MW were reflected in PV values. It was found that there was a 6.3 º/s reduction in PV when task complexity assessed by MWT increased by 10.6 and performance was also affected (6 delayed answers).

However, there was one limitation in this work. It was not possible to distinguish between the effects of task complexity and time-on-task [TOT], due to the nature of the experimental design. Indeed, to avoid any effect of task switching during the experimental session, the order of task complexity levels was not balanced across participants.

On the basis of these results, it was designed a well-controlled experiment **(Chapter IV,** Di Stasi et al., submitted a) to surmount the methodological problem encountered in the previous studies, and particularly the influence of TOT on the disruption of the main sequence rules. In this study screen visual configuration was manipulated between groups to create two different levels of task complexity. Also the TOT was manipulated (within group), participants had to perform the same simulation (eye movement and subjective measure were recorded during the 1st and 10th trial) ten times. In more detail, the Firechief (Omodei & Wearing, 1995) incident simulator (microworld) was chosen as a complex and dynamic problem-solving task. Microworlds are an appropriate research environment to test hypotheses about MW because they are based on simulations of real tasks that change dynamically and are designed to reproduce the important characteristics of real situations. The experiment was set up to test the validity and sensitivity of PV compared with the results of performance and subjective ratings in response to the main manipulations. Within the limits imposed by the experimental task and the sensitivity of the no-psychophysiological measurements; PV was sensitive to the manipulations of the screen configuration and TOT. Consistent with previous studies, we found that saccadic movements were lower (276 º/s vs. 290 º/s) while mental workload was higher, and with an increase of time on task; i.e. tiredness (1^{st} trial 287 º/s vs. 10^{th} 279 º/s).

The major flaw of the study is the fact that to test the sensitivity of the PV the eye movements were only recorded in the first and last trial (resulting in 2 x 260 sec of eye movement data per subject). The conclusion of this work would be more convincing, if eye movement data would be available for the complete experiment. For this reason in the follow experiments eye-movements were recorded for the entire duration of the experimental session.

Chapter V and Chapter VI represent the core of the research part of this doctoral thesis. The general thesis aims, background of the research problem, and research methodology are described in Chapter V. In Chapter VI is addressed the evidence that the PV could be used as sensitive and valid on-line index of driver mental state.

In **Chapter V** (Di Stasi et al., submitted d) describes an experiment which aim was to prove the effect of mental fatigue (or TOT) in driving context. In this experiment the results showed the great potential of the PV as a vigilance screening tool, during performing a driving simulation. The general aim was to propose an online measure of mental fatigue in drivers. Eye movements were recorded while the drivers were engaged in a fixation-visual task administered before and immediately after 2 hour long driving task as well during the driving task. The subjects were asked to fill the Stanford Sleepiness Scale [SSS] as a global measure of sleepiness, the Chalder Fatigue Scale [CFS] as a measure of fatigue, and the Mental Workload Test (MWT) as a measure of mental workload. Also the subjective measures were administered before, immediately after the driving task. Results showed that scores at the SSS and CFS after the driving task were significantly higher than before. No effect of measuring times was found on the mental workload scores, instead. With regards to the saccadic parameters, authors found that duration of saccades longer than 10° reduced from the first to the second measuring time, and that peak velocity of saccades longer than 7.5° decreased from the first to the second measuring time (before driving 388 º/s vs. after driving 356 º/s). The same tendency was present on the on-line recording data, a gradual decrement of the saccadic peak velocity after the first hour of driving. Also on the basis of a further analysis carried out on data recorded during the driving task, it was possible to conclude that peak velocity is a valid measure of the variation of mental fatigue during long-lasting and repetitive tasks. The chapter concludes 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.

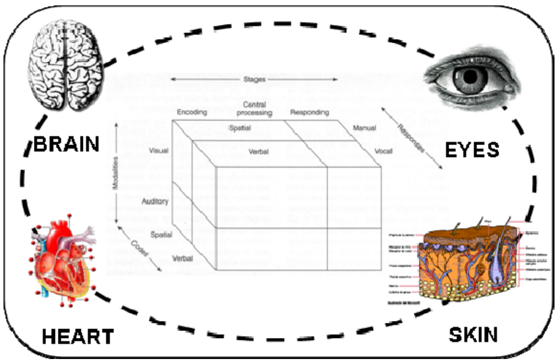
In the previous investigation it was showed that the effect of fatigue becomes clear after approximately one hour of driving, for this reason to avoid any confounding effect on the PV, the global duration of the next experiment was less than 60 minutes. **Chapter VI** (Di Stasi et al., 2010 d) describes similar results of Chapter V but obtained in a more complex experimental setting. In this study, it was demonstrated that PV was sensitive to variations in MW during ecological driving tasks, showing again an inverse relation between PV and task complexity. In this experiment, three different levels of task complexity (low, medium and high) were created by manipulating traffic density and adding a secondary task. Traffic density could either be low (no other cars) or high, and it was assumed to affect the load of information processing (Wickens, 2002). As a secondary task, potentially hazardous situations were produced by pop-up events that appeared in the central field of view. The events were red squares and rectangles. Each type of event was associated with a specific reaction. Participants were asked to press the left or the right button of the steering wheel in response to the squares and rectangles, respectively. Low task complexity was defined as driving with low traffic density and no secondary task. Medium task complexity involved low traffic density and a secondary task. In the high complexity task condition, high traffic density was combined with the secondary task. To disentangle mental workload and fatigue, the order of tasks was varied in the following way: all subjects started with low task complexity, while the order of medium and high complexity tasks was balanced across the subjects. Results showed that PV decreased by 7.2 º/s as the MWT score of MW increased by 15.2 and reaction time for the secondary task increased by 46 msec. Saccade duration and velocity were not affected by differences in task complexity. The design of this experimental investigation allowed the authors to differentiate between the effects of TOT and changes in MW from the same dataset. As expected in this experiment, no effect of fatigue was found.

Finally, **Chapter VII** (Di Stasi et al., submitted c) provides the general conclusions of this doctoral thesis as well as a short overview of recent experimental and theoretical findings, which relates the results of more than one century of psychological research on saccade dynamics behaviour to human factor investigations. Considering the earliest findings of Dodge and Cline (1901) and the latest one (for example Hirvonen et al., 2010), a “global picture” about this index and its application in applied and basic context is showed. Also future guidelines and application for applying the saccadic peak velocity are described.

4.1. DOCTORAL THESIS SQUEMATIC OVERVIEW

INTRODUCTION (Chapter I)

Saccadic Peak velocity: the necessity of on-line attentional index



A schematic overview/comparison on the mental workload indices (from subjective to psychophysiological measures) is presented. Is presented also a short revision and justification for the election of saccadic peak velocity as alternative operator attentional state index. Experiments A, B, C, D and E (see below) are also described

EXPERIMENTAL SERIES (Chapters II, III, IV, V, VI)

EXPERIMENT A

The first approximation to the problem

Experimental stimuli	Methods

Session: ca. 1 hour

Independent variable:

Risk Behaviour (2 levels: low & high)

Dependent variables:

Saccade & Fixation num (number)

Saccade & Fixation Duration (ms)

Saccade Amplitude (º)

Pupil Diameter (system unit)

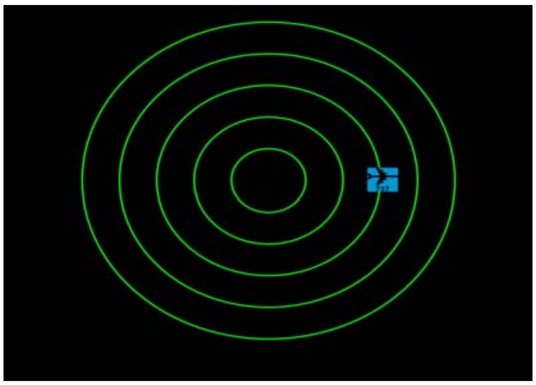
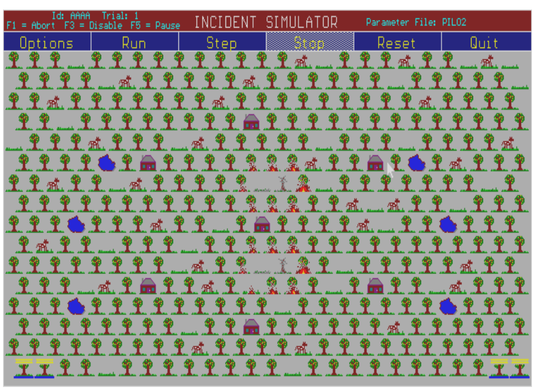
Ratio [Peak/ Saccadic Number](º/ms)

Mental workload Test (score)

Main Results: Negative correlation between the MWT scores and saccadic peak velocity values for the high risky group

EXPERIMENTS B and C

Applying the Saccadic Bin Analysis in well controlled ecological tasks

Experimental stimuli	Methods
	**Session:** ca. 1 hour **Independent variable:** Task Complexity (3 levels: low, medium & high) **Dependent variables:** Main sequence (º; º/s; ms) Mental workload Test (score) Delayed answers (number) Error (number) **Number of bins:** 5 (from 0.01º to 7.5º) **Main Results:** Decrease of the PV as increase of task complexity.
	**Session:** ca. 1 and 1/2 hour **Independent variables:** Task Complexity (2 levels: low & high) Time-on-Task (2 levels: 1st trial vs 10th) **Dependent variables:** Main sequence (º; º/s; ms) Mental workload Test (score) Performance score on primary task (score) **Number of bins:** 8 (from 0.01º to 13.9º) **Main Results:** Effects of Task Complexity and Time-on-Task on the PV value (decrease of PV)

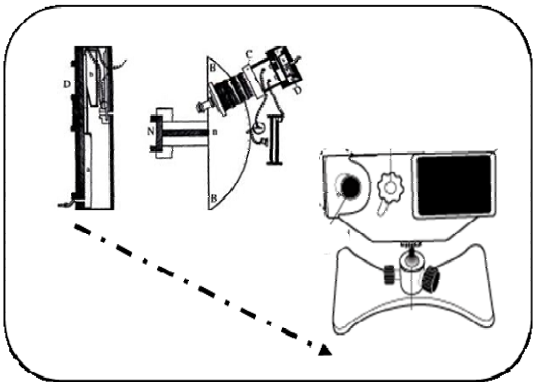
EXPERIMENTS D and F

Saccadic peak velocity as a driver attentional index

Experimental stimuli	Methods
	**Session:** ca. 3 hours **Independent variables:** Time-on-Task (3 level 1st, 2nd & rest) **Dependent variables:** Main sequence (º; º/s; ms) Mental workload Test (score) SSS and CSF Questionnaires (score) Mean Speed (km/h) **Number of bins:** 9 (from 2.5º to 20º) **Main Results:** Decrease of the PV as increase of time-on-task (no secondary effect of Mental workload as reported on MWT scores).
	**Session:** ca. 1 hour **Independent variables:** Task Complexity (3 levels: low, medium & high) Time-on-Task (2 level 1st vs 2nd) **Dependent variables:** Main sequence (º; º/s; ms) Mental workload Test (score) Reaction time on secondary task (ms) Mean Speed (km/h) **Number of bins:** 9 (from 0.01º to 15.9º) **Main Results:** Decrease of the PV as increase of task-complexity (no confounding effect of Time-on-Task as reported on the analysis of session order).

CONCLUSIONS (Chapter VII)

General conclusion: from a mini-review to some personal “speculations”



Conclusions of the project thesis and a mini review about the history of the saccadic peak velocity from the earliest findings of Dodge and Cline (1901) to the latest one (Hirvonen. 2010), are presented. A “picture” of the knowledge developing about this index and its application in applied and basic context is showed. Also future guidelines and application for applying the saccadic peak velocity are described.

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CHAPTER II.

The first approximation to the problem

Risk behaviour and mental workload: Multimodal assessment techniques applied to motorbike riding simulation

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ABSTRACT

We present data from an ongoing research project on the cognitive, emotional and neuropsychological basis of risk behaviour. The main aim of the project is to build a model of risk behaviour so that if we know certain cognitive, behavioural and emotional variables, we will be able to predict decisions made in the face of uncertainty and risk, with the final goal of designing programs for evaluating, preventing and controlling risk behaviour. The objective of the present study was to look for individual differences in hazard perception during a static riding simulation and their relationship with mental workload. We used a multidimensional methodology, including behavioural, subjective and physiological data. The behavioural measures were obtained in a static riding simulation during eight hazard situations. We evaluated whether eye activity measures correlated with cognitive workload and different types of risky behaviours. Eye movement parameters were measured using a video-based eye tracking system. We found that risk-prone individuals showed specific patterns of risky behaviours and that peak of saccadic velocity and subjective mental workload indexes were both reliable indicators of risk proneness. Mental workload was higher for participants showing attitudes to risk behaviours probably because of a lack of conscious awareness of specific cues indicating dangerous scenarios.

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1. INTRODUCTION

Improving road safety is an important issue. Every year, about 47,000 people are killed in the European Union (EU) as a result of road accidents (Janssen & Attané, 2004). Contributing factors to crashes are commonly classified as human, vehicle or roadway/vehicle/environmental (Knipling, 2005). Most accidents are attributed to human factors (90–95%, Todoskoff et al., 1999), which as a single cause are responsible for 65% of road accidents (Kenny, 1995). Inattention has been identified as the leading primary cause, accounting for 25–56% of the total number of accidents (Petridou & Moustaki, 2000; Sánchez et al., 2006). Proportionally motorcycles are the vehicles most frequently involved in road accidents (European Transport Safety Council [ETSC], 2003). When there is a collision with another road user, motorcyclists are responsible for 26% of these accidents (Assing, 2002).

Riding a motorcycle is a dynamic and complex psychomotor activity demanding simultaneous processing of information on different cognitive levels as well as a variety of physical activities in a constantly varying setting. Therefore, in any motorcycle road accident, the cause may be attributed to a combination of defects or defective performance in a number of factors (Kenny, 1995) such as lack of skills because of inexperience, youthfulness or lack of maturity, young drivers' proneness to risk-taking, and driving in unfamiliar environments (Hole, 2007; Triggs, 2004).

Driving safety calls for changes in drivers' behaviour and increasing responsibility for their actions and decisions. It is therefore necessary to identify the risks related to the driver (Guzek et al., 2006). Our study aimed to unveil the relationship between motorcycle drivers' risk behaviour and mental workload using a multidimensional methodology that incorporated psychophysiological, subjective and performance data in a static riding simulator.

Evaluating drivers/riders on roads is dangerous and expensive and it is difficult to obtain repeatable results. Simulators create an environment without threat for drivers and other road users (Chang et al., 2006; Hoskins et al., 2002). They put the driver in a realistic ''environment" (Koustanaï & Aillerie, 2004), can be used to study dangerous situations frequently difficult or impossible to reproduce in actual road condition (Brünger-Koch et al. 2006; Champion et al., 2002), and allow both training of novel riders and training of experienced riders in coping with dangerous situations, as well as assess the riding ability of older riders (Cossalter et al., 2006).

2. RISK BEHAVIOUR AND MENTAL WORKLOAD IN RIDING

Riding is a multi-task, complex behaviour that includes primary and secondary abilities. Typical primary task are steering, managing the throttle and brakes, controlling the speed, lane choice, navigating and hazard monitoring. Secondary ones are, for example, those which must be performed en route to a destination like way-finding task. (Young & Angell, 2003). Riding quality depends on operator awareness of the road situation.

Riders' abilities can be evaluated by behavioural and psychophysiological measures (Boer, 2005). Behavioural evaluation includes ''misbehaviours" and mistakes. Misbehaviours are traffic rule violations such as alcohol abuse or exceeding the speed limit. Mistakes are failures in processing the road situation, such as not seeing the speed limit mark or underestimating the vehicle-to-vehicle distance. However, the border between misbehaviours and mistakes is fuzzy: red-light running may be classified as a rule-based misbehaviour if intentional but a skill-based mistake if not. Rimmo and Hakamies (2002), following Reason's taxonomy (1990), proposed four error types: violations (deliberate deviations), mistakes (intended action with unintended consequences), inattention errors (unintended action resulting from recognition failure) and inexperience errors (unintended action resulting from lack of knowledge or skill). All these errors involve risky behaviours that we need to understand in order to prevent accidents and fatalities.

Risk is the extent to which there is uncertainty about whether potentially significant and/or disappointing outcomes of decisions will be realized. The three key dimensions of risk are outcome uncertainty, outcome expectations and outcome potential (Sitkin & Pablo, 1992). The ''risk as feelings" hypothesis states that risk behaviour depends on two systems (rational–analytic and experiential–affective) that jointly determine the individual's risky decisions (Damasio, 1994; Kahneman & Frederick, 2005; Sloman, 1996). The rational–analytic system is slow, conscious and symbolic and requires effort (Slovic et al., 2004). The experiential–affective system is effortless, fast, based on successful situation–action links and oriented to immediate actions (Slovic et al., 2004). The combined amount of mental effort required for the two systems is called ''mental workload" (Hamilton et al., 1979; Sheridan, 1979).

Mental workload has long been recognized as an important factor in human performance in complex interactive systems (Vitense et al., 2003) and has been defined as the amount of cognitive capacity required to perform a given task (O'Donnell & Eggemeier, 1986). It therefore refers to ''a composite brain state or set of states that mediates human performance of perceptual, cognitive and motor tasks" (cit. Parasuraman & Caggiano, 2002, p.17). In general, mental workload is considered to be a multidimensional construct involving interactions between the task and system demands, the operator (including mental and emotional capabilities) and the environment (Sanders, 1979; Schlegel, 1993).

In transportation research, mental workload is commonly defined as the effort required to maintain the driving state within a subjective safety zone (Boer, 2005). The boundaries of the safety zone depend on the decisions made by the road users in relation to benefits and costs. In this field, mental workload is commonly measured by the NASA-Task Load Index [NASA-TLX] questionnaire (Hart & Staveland, 1988) or the Driving Activity Load Index [DALI] questionnaire (Pauzié & Pachiaudi, 1997).

Eye activity is also a common indicator of whether the user is processing information about driving (Chapman & Underwood, 1998; Velichkovsky et al., 2002; Velichkovsky et al., 2002). Saccadic response, especially peak of saccadic velocity, is related to mental workload in dynamic and complex decision-making and could be a possible alternative to pupil diameter (Di Stasi et al., 2008; Di Stasi & Antolí, 2008; Di Stasi et al., 2007). Some research has shown a relationship between saccadic dynamics and mental activation (Galley, 1989, 1998). For example, task complexity (Smit & Van Gisbergen, 1989) and some task variables – such as the presence of a second task – can influence peak of saccadic velocity (Galley, 1985). Furthermore, in visual performance tasks, saccadic velocity varies with the state of mental activation of the subject (App & Debus, 1998; Debus et al., 1999) and is related to natural fluctuation in alertness (Becker, 1989; Thomas & Russo, 2007), vigilance (Fafrowicz et al., 1995), mental fatigue (Schmidt, Abel, Dell'Osso & Daroff, 1979) and mental workload (Churan et al., 2003; Di Stasi et al., 2007, 2008; Mizushina et al., 2007).

In this paper we present data from a study on risk behaviour and mental workload in a riding simulation task. We are building a comprehensive model of risk behaviour so that, knowing a certain number of individual cognitive and emotional variables, we will be able not only to predict risky decisions but also to design programs for evaluating, preventing and controlling risky behaviours. Young inexperienced students with no driver's licence had one training and one test trial in the Honda Riding Trainer (HRT). Mental workload was assessed by the Mental Workload Test (MWT), a Spanish adaptation of the NASA-TLX test (Cañas, et al., 2001) and eye movement parameters. We looked for relationships between the dimensions of mental workload, eye activity and riding performance, including response to risky situations.

3. METHODS

3.1. PARTICIPANTS

That young inexperienced drivers are over-represented in road crashes is well established (Dols et al., 2001). Their risk ranges from 2 to 4 times that of mature experienced drivers (Triggs, 2004). Consequently, the participants of this study were young people without riding experience or a driver's licence. A total of 60 Granada University undergraduates (age range 18–32 years, 31 females, 29 males) participated in the study for course credit. All participants signed a consent form that informed them of the risks of the study and the treatment of personal data.

3.2. INSTRUMENTS

The EyeLink II system (SR-Research Ltd.) was used to record participants' eye movements. The recording rate was 500 Hz. Calibration was done before each riding session.

Participants were tested on the Honda Riding Trainer (HRT) (Honda Motor Co.) This is a recent ‘‘low-cost” non-immersive virtual reality riding simulator. The HRT was designed to teach psychomotor and cognitive skills to novice riders and provide a tool for evaluating riding ability. Two recent studies demonstrated that the HRT improves hazard perception and awareness in teenagers (Bastianelli & Vidotto, 2007; Vidotto & Bastianelli, 2008). The system logs data for each trial and provides a graphic report of specific performance measurements such as accident points, road-code violations, riding control response, speed and lane deviations.

The HRT used in this study features a simple moped mock-up with a seat, handlebar, pedals, accelerator, brakes, turn indicators and claxon. The road scenario is displayed on a 19 in. LCD screen, located in front of the rider, seated on the HRT a motor seat. The participants performed the simulation at a normal viewing distance from the screen (approximately 80 cm), which was placed in an ortho-frontal position to the observer. Only the frontal view was used. The human–machine interaction takes place via the devices that are typically present in an actual moped, so the primary controls of the simulator were physical. The handlebar provided haptic feedback and mechanical response. Speed, activation of the turn indicators and right/left rear mirror view were displayed on the monitor. Loudspeakers located in front of rider at about 2 m from the ground provided engine and other acoustical feedback.

Riding scenarios were designed to train dynamic and complex time-critical riding skills, including situational awareness, hazard perception and risk assessment, and involved hazardous pedestrian, traffic and signal conflicts. A hazard is any object, condition or situation that tends to produce an accident when drivers fail to respond usefully; hazardous situations are combinations of conditions and objects, usually with a temporal feature (Dewar et al., 2007). In this study, potential hazard situations were produced mainly by incoming vehicles (cars and motorcycles) from different sites and unexpected obstacles on the road (Fig. 1). An automatic motorcycle (moped 49 cc., maximum speed 60 km/h) and three specific scenarios from the HRT visual database (Training 1 "Free Town Riding"; Training 2: "Country Road"; Experimental scenario: "Main Street") were selected.

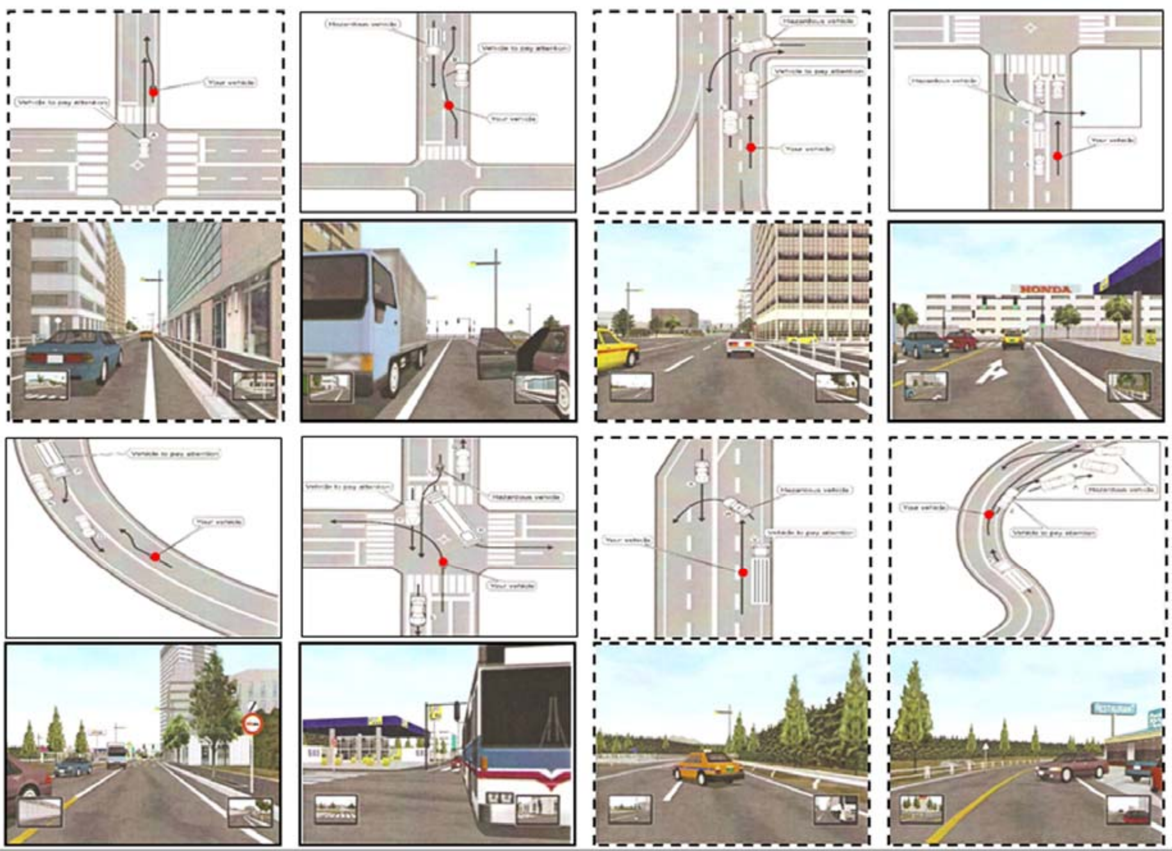

Figure 1. Hazardous situations (up) schematic representation (red dot participant vehicle) and (down) eye-view [in sequential order - clock sense]: checking the rear view when starting (1); stopping vehicle opens the door (2); forward vehicle brakes hard due to a crossing vehicle (3); vehicle crosses the road without stopping (4); on-coming vehicle crosses the centre line (5); on-coming vehicle turns when the moped turns left (6); taxi makes a U turn (7); vehicle turns left from a roadside facility (8) [source: HRT Manual]. Scenes 1, 3, 7 and 8 are part of S1 group; scenes 2, 4, 5, and 6 are part of S2 group (for more details see analysis paragraph).

3.3. DESIGN

The study proceeded in three stages, with two training rides and one test ride. The first training session showed participants how to operate the HRT and the second how to manage the motorcycle in a complex situation.

Training 1 scenario, ‘‘Free Town Riding”: This ‘‘adjustment run” required the participants to ride a free circuit along a road for about 5 min, without traffic, obstacles or hazardous situations. It allows participants to get used to the input/output devices. An experimenter showed the correct function of all devices and helped participants understand the simulator.

Training 2 scenario, ‘‘Country Road”: The second training stage involved riding for about 5 min on a country road circuit with dual carriageway, mixed flow traffic and intersections. Eight potentially risky situations were implemented in this run. Again, the experimenter helped participants by describing the correct procedure in case of accidents and answering any questions related to the simulator.

Test scenario, ‘‘Main Street”: Participants ride the first training scenario again and are then immediately asked to ride for about 5 min on an urban circuit, with dual carriageway, mixed traffic flow, intersections and eight potential accident situations (similar to those in the Training 2 scenario). The experimenter helped only participants who had problems.

3.4. PROCEDURE

The participants were told that the purpose of the experiment was to evaluate their behaviour in a realistic road environment. They were taught how to use the riding simulator and given instructions about the driving tasks. Each participant was asked to follow the road rules to the best of his/her ability. If a rider had an accident, a crash sound was heard, visual information concerning the crash was given and the system reset the moped back on the road. No penalty structure was included, because we wanted to mimic ‘‘normal” riding behaviour (Stein, 1995). A recorded voice gave the riders instructions in Spanish. They completed the study over two days, with one training and one test day, totaling about 2 h.

On the first day the participants performed two training sessions, on the second one they completed the test session, in which they were seated in the HRT, wore the eye tracker headband and rode the Training 1 (baseline) and Test circuits. After calibration, eye activity was recorded throughout the entire ride, including the training and the test stages. The eye tracker was calibrated again at the end of each run. After the tes, including the training and the test stages. The eye tracker was calibrated again at the end of each run. After the test ride, participants were asked to fill in the Mental Workload Test. Debriefing was done at the end of this experimental session.

3.5. DEPENDENT VARIABLES

We used a multiple measures approach that included performance, psychophysiological and subjective measures for monitoring rider's behaviour.

3.5.1. PSYCHOPHYSIOLOGICAL DATA

Psychophysiological eye movement data were used to estimate mental workload in the baseline and test sessions. We measured the following indexes of eye movements: saccadic number, saccadic amplitude (visual degree), saccadic duration (ms), peak of saccadic velocity (visual degree/s), fixation number, fixation duration (ms) and pupil diameter (unit system).

Traditional methods of analysis of ocular movements focus mainly on the separation of fixations from saccades (Salvucci, 1999). In the present study, the selection of saccades was based on temporal criteria (saccade, range from 10 to 99 ms and fixation, range from 100 to 2.500 ms). The indices with their respective parameters outside the interval have been rejected for the analysis (Rayner, 1998).

3.5.2. HRT PERFORMANCE DATA

In each simulator scenario, riding performance, errors, accidents and road-code violations were automatically logged.

However, since different kinds of errors can occur at different frequencies and the importance of any violations can vary, riding performance was scored with a four-grade scale: 1 = safe behaviour (no accidents, avoided hazards without hard braking or coming too near, followed the speed limits), 2 = precaution behaviour (didn't follow the speed limit, applied the brakes hard, came near other vehicles), 3 = hazardous behaviour (hard breaking near other vehicles) and 4 = accident.

3.5.3. SUBJECTIVE MEASURES

Two different sets of questionnaires were used, the Ergonomics Evaluation Questionnaire (EEQ) and the Mental Workload Test (MWT). The EEQ is a comprehensive tool aimed at collecting ergonomic evaluation about dynamic riding/driving simulation and the human–machine interface. It was developed and adapted for this study by the Cognitive Ergonomics Group (CEG). The instrument asked for an evaluation on 13 scales (21 points) of a visual analogue scale ranging from 0 = ‘‘inadequate” to 100 = ‘‘adequate” for most items but ‘‘nothing” to ‘‘much” for the simulator sickness items) For this study the test was composed of 23 items divided in six subsets: (1) simulation module (two items); (2) interaction with the simulator (three items); (3) simulation scenarios (four items); (4) visual data-base (five items); (5) sounds effect (four items); and (6) simulator sickness (five items). It also collected demographic data (age, sex) and data about personal computer (PC) game experience and bicycle riding experience.

The Mental Workload Test was developed by the CEG (Cañas et al., 2001, Cronbach’s alpha, 0.68, Fajardo, 2001) and was based on two pre-existing instruments, the NASA-TLX (Hart & Staveland, 1988) and the Workload Profile (Tsang & Velazquez, 1996). The instrument asked participants to make an evaluation on 13 scales. Each scale was presented as a visual analogue scale with a title and a bipolar descriptor [low/high] at each end. Numerical values were not displayed, but values ranging from 0 to 100 [21 points] were assigned to scale the position during data analysis. The 13 scales/dimensions were perceptual/central demand, answer demand, verbal demand, spatial demand, visual perceptual demand, auditory demand, manual demand, vocal demand, physical demand, temporal demand, performance, effort and frustration level. The participants filled in the MWT after they finished the test session.

4. RESULTS

Eight participants were excluded from the analysis because of equipment failure. The rest were assigned either to the high-risk or the low-risk group according to the riding scores provided by the HRT system for each of the eight potentially risky situations. We assumed that two scenes (e.g., E1 and E2) were similar when the probability of scoring high in E1 given a high score in E2 was greater than the probability of scoring high in E1 given a high score in the rest of the scenes. This revealed two groups of scenes: scenes 1, 3, 7, and 8 (hereafter S1 scenes) and the other scenes (hereafter S2 scenes). The S1 and S2 scores were used to classify participants as belonging to a high-risk group if the S1 and S2 scores were above the S1 and S2 medians or a low-risk group if the scores were below the medians. The grouping of scenes and classification of participants was validated by a K-means cluster analysis and coincided with a grouping based on a scene difficulty index, computed as the proportion of participants who scored equal or higher than 3 (hazardous behaviour).

4.1. PERFORMANCE DATA

A 2 (risk group: high/low, between subjects) 8 (HRT scenes, S1 and S2, within subjects) analysis of variance showed main effects of risk group [$F(1,50)=41.014$, $MSE = 0.163$, $p < 0.01$] and HRT [$F(1,50)=116.821$, $MSE = 0.174$, $p < 0.01$]. No interaction between the two factors was observed [$F(1,50)=2.941$, $p > 0.09$] (Fig. 2). As expected, because our clustering criteria, high-risk subjects scored higher than low-risk ones in both S1 and S2 HRT scenes (Fig. 2).

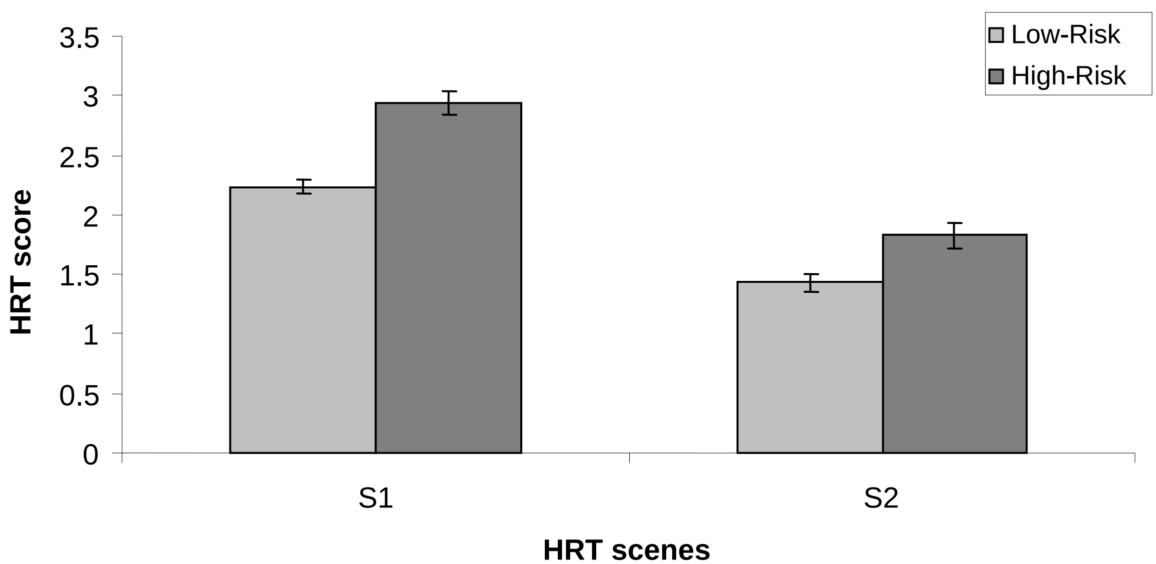

Figure 2. Average HRT scores for high-risk and low-risk groups in S1 (scenes 1, 3, 7, & 8) and S2 (scenes, 2, 4, 5, & 6). Vertical bars are the standard error of mean.

We explored whether risk-proneness changed with increasing experience by averaging the two first scenes (T1) and the last two ones (T2). A 2 (risk group: high/low) ˥ 2 (HRT scenes position, T1 and T2, within subjects) analysis of variance showed that risk group [$F(1,50)=33.351$, $MSE = 0.285$, $p < 0.01$], HRT scenes position

[F(1,50)=5.473, MSE = 0.222, $p < 0.025$] and the interaction of the two factors [F(1,50)=5.473, MSE = 0.222, $p < 0.025$] were reliable. HRT scores were higher in the last than in the first scenes only for the high-risk group [F(1,50)=7.90, MSE = 0.222, $p < 0.01$]. These results suggest that as time in the simulator increased, risk-prone people appeared to increase the frequency of risky behaviour (Fig. 3).

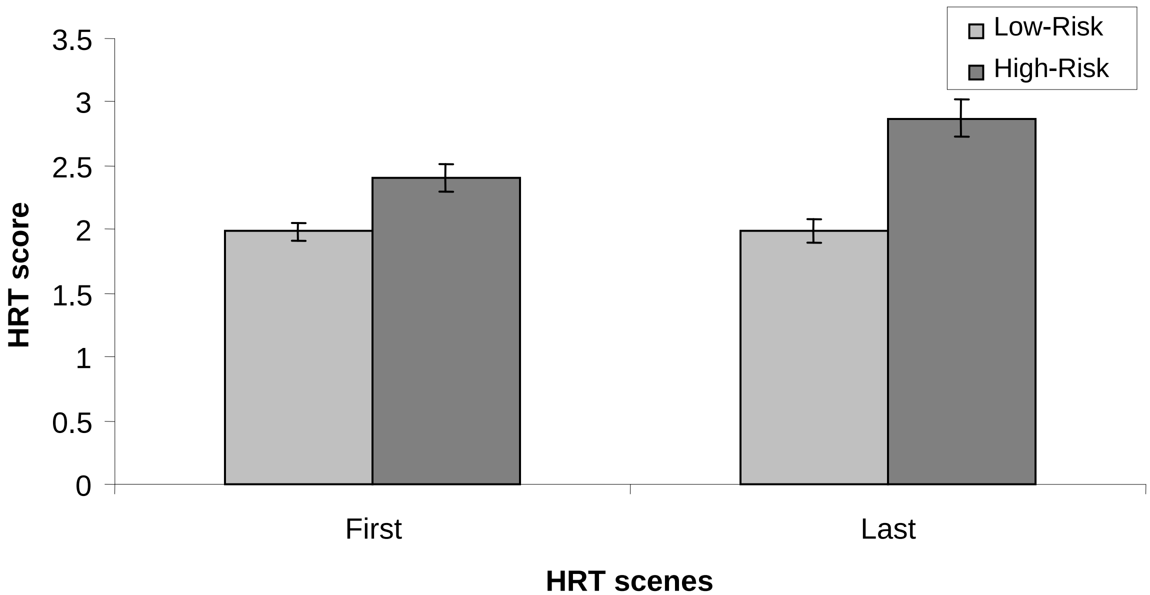

Figure 3. Average HRT scores for high-risk and low-risk groups in the first scenes (1 & 2) and the last ones (scenes, 7 & 8). Vertical bars are the standard error of mean.

4.2. EYE MOVEMENTS

Eye movement indices were computed as the difference between the test index score and the baseline score. Peak of saccadic velocity was normalized by saccade number. Three further subjects were excluded from the analysis because of EyeLink II failures during the baseline recording. Difference scores were submitted to a multivariate analysis of variance, using as between subjects' factor the risk group. Differences between groups were significant (Wilks' K = 0,72, F(7,41) = 2.56, $p < 0.05$). One way univariate analysis of variance showed that the high-risk group had a lower saccade number

[F(1,47) = 5.73, MSE = 9581.4, $p < 0.05$], shorter saccade duration [F(1,47) = 4.504, MSE = 8.3, p = 0.05] and higher peak of saccadic velocity [F(1,47) = 7.088, MSE = 0.015, p 6 .04] compared to the low-risk group (Fig. 4).

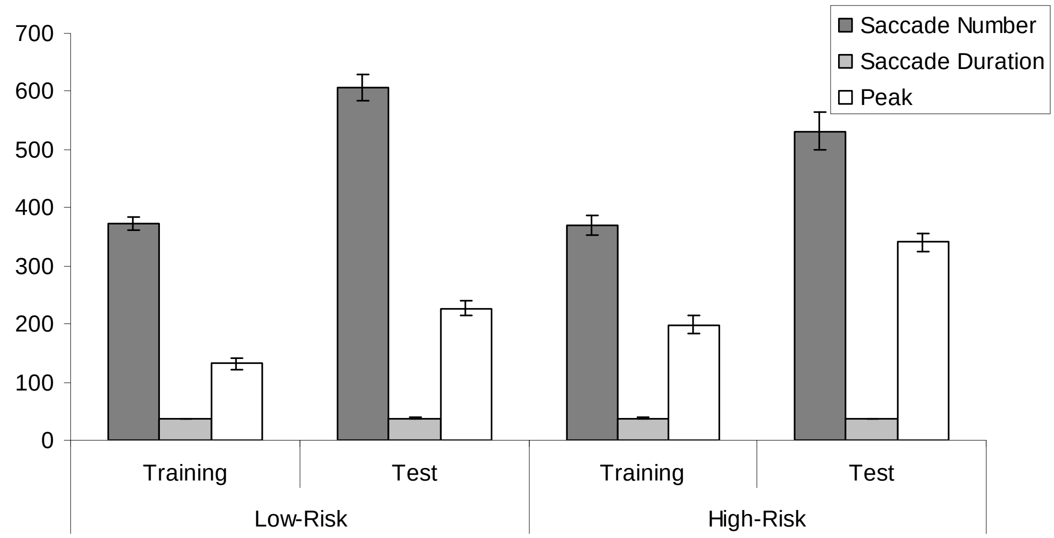

Figure 4. Average saccade number, saccade duration (msec), and peak of saccadic velocity (visual degree/sec) for high-risk and low-risk groups. Vertical bars are the standard error of mean.

4.3. SUBJECTIVE RATINGS OF MWT AND EEQ

The scores in the Mental Workload Test were submitted to one way univariate analysis of variance. Between groups differences were observed only for perceptual/central demand [$F(1,49)=4{,}277$, $MSE = 424.94$; $p < 0.05$] and answer demand [$F(1,49)=4{,}339$; $MSE = 389.81$, $p < 0.05$]. In both dimensions, higher average scores were observed in the high-risk group than in the low-risk one (Fig. 5). The scores in the EEQ were submitted to one way univariate analysis. No differences were observed.

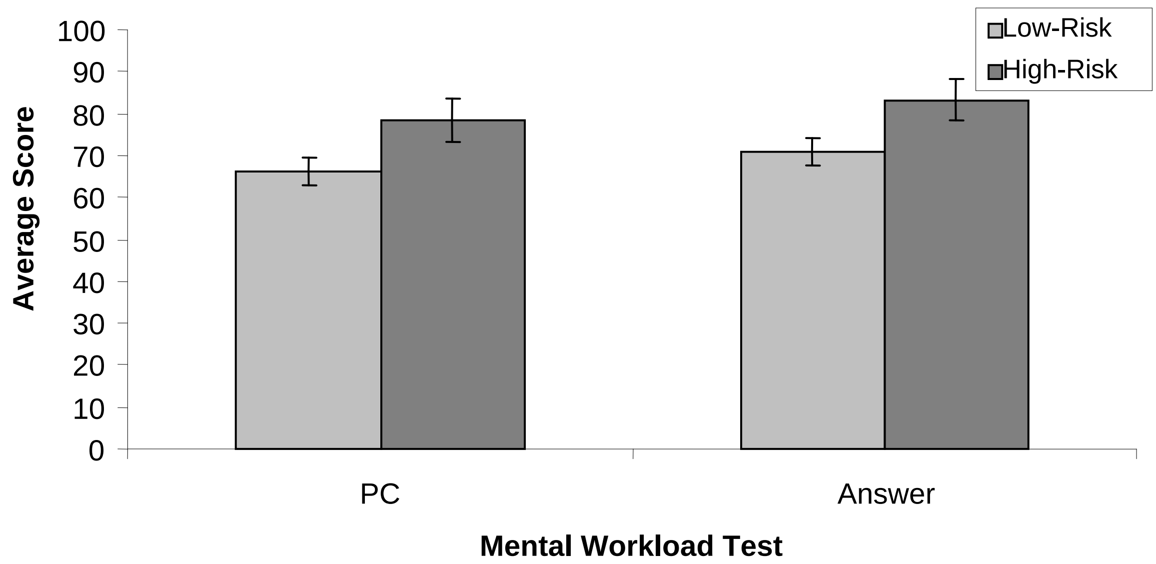

Figure 5. Subjective ratings of Perceptual/Central (PC) and Answer Demands for high-risky and low-risky participants. Vertical bars are the standard error of mean.

4.4. SUBJECTIVE MENTAL WORKLOAD AND EYE MOVEMENTS

The relationships between the scores in the scales of the Mental Workload Test and eye movement indices were computed separately for the high-risk and low-risk groups. Both the number and the sign of the significant linear correlations were dependent on the risk group (Tables 1 and 2). In general, negative correlations were observed in the high-risk group, especially for the peak index. This indicates that in the high-risk group, the lower the peak index, the higher the mental workload (perceptual/central, verbal, spatial and auditory demand, performance, effort and frustration) but in the low-risk group the higher the peak index, the higher the verbal and the physical demand.

Table 1. Linear correlations between subjective (Mental Workload Test) and Psychophysiological (Eye movements) indices of mental workload for the low-risky group.

	Saccades				Fixation		Pupil
	Number	Duration	Amplitude	Peak	Number	Duration	Size
PC[1]	-0.06	0.10	0.16	0.16	0.14	-0.1	0.12
Answer D.	-0.07	0.13	-0.01	0.20	0.00	-0.08	0.24
Verbal D.	-0.20	0.07	0.05	0.49*	-0.13	0.31	0.14
Spatial D.	-0.19	0.00	0.02	0.31	-0.16	0.00	0.01
Visual D.	-0.17	-0.10	-0.08	0.26	-0.13	0.01	0.12
Auditory D.	-0.21	-0.21	-0.05	0.33	-0.23	0.15	0.31
Manual D.	-0.12	-0.01	-0.14	0.26	-0.03	-0.07	0.21
Vocal D.	-0.17	-0.30	-0.03	0.26	-0.18	0.23	0.22
Physical D.	-0.37*	0.14	-0.01	0.47*	-0.27	-0.03	0.11
Temporal D.	-0.32	-0.04	-0.10	0.29	-0.14	0.05	0.03
Performance	-0.09	0.10	-0.23	-0.06	-0.11	-0.2	0.23
Effort	-0.19	0.26	-0.12	0.04	0.02	0.02	0.24
Frustration	-0.23	0.44*	0.17	0.15	-0.17	0.04	0.07

* Significant correlations (p<0.05).

Table 2. Linear correlations between subjective (Mental Workload Test) and Psychophysiological (Eye movements) indices of mental workload for the high-risky group.

	Saccades				Fixation		Pupil
	Number	Duration	Amplitude	Peak	Number	Duration	Size
PC[1]	0.39	-0.15	-0.13	-0.67*	0.47	0.08	-0.10
Answer D.	0.29	-0.02	-0.06	-0.48	0.35	0.10	-0.14
Verbal D.	0.51*	0.02	-0.22	-0.74*	0.47	-0.17	-0.09
Spatial D.	0.23	0.07	-0.16	-0.54*	0.27	-0.04	-0.46
Visual D.	0.28	-0.12	-0.47	-0.67*	0.32	0.09	-0.16
Auditory D.	0.26	0.22	-0.15	-0.57*	0.22	-0.02	-0.12
Manual D.	0.09	0.09	-0.22	-0.48	0.11	0.19	-0.12
Vocal D.	0.09	0.23	0.33	-0.11	-0.02	-0.15	-0.51*
Physical D.	0.17	0.07	0.07	-0.41	0.17	0.03	-0.07
Temporal D.	0.35	0.32	-0.01	-0.46	0.29	-0.23	-0.20
Performance	0.60*	0.10	-0.01	-0.54*	0.55*	-0.47	-0.19
Effort	0.33	-0.26	-0.19	-0.66*	0.40	0.02	-0.28
Frustration	0.31	-0.20	-0.28	-0.56*	0.38	-0.02	-0.12

[1] PC stands for Perceptual/Central Demand. * Significant correlations (p<0.05).

5. DISCUSSION

This study was intended to determine whether eye activity indices and subjective mental workload depended on the riskproneness of untrained naïve motorcycle riders without a driving licence. There were four main findings. First, high-risk participants tended to increase their risk behaviour as their time in the simulator increased but low-risk participants do not change their behaviour over time. One explanation is that high-risk subjects became more tired or less able to pay attention to the task over time compared to low-risk subjects. Alternatively, high-risk subjects may increase their tendency to choose risky behaviours as they gain experience. Further research is needed to discriminate between these two alternatives.

Second, high-risk participants had fewer saccades of shorter duration and higher peak of saccadic velocity than low-risk participants. We think that this is an index of a shallow processing of the task, because visual exploration of the riding environment involves locating objects and lights and assessing the apparent speed of moving objects and the distance between vehicles, among other things, which calls for a high number of saccades. Third, high-risk subjects appeared to tap into only two dimensions of subjective mental workload: perceptual/cognitive demands and answer demands. Risk-prone participants felt riding required a higher mental workload than low-risk individuals. Finally, our data indicated that subjective and eye motion measures of mental workload were better correlated in high-risk than low-risk participants. Peak of saccadic velocity was a better indicator of subjective mental workload than other eye movement measures, because it correlated with 61% of the subjective scales in the high-risk group. The negative correlations of peak of saccadic velocity and subjective scales of mental workload suggested that, given a high level of risk-proneness, higher peaks were associated with a lower level of subjective workload. Importantly, when risk-proneness is low, the opposite result was observed. Risk-proneness is therefore an important factor for convergence between subjective and objective measures of mental workload, especially peak of saccadic velocity (see Di Stasi et al., submitted).

From these preliminary results, it is possible to conclude that high-risk participants experienced more mental workload, probably as a consequence of a lack of conscious awareness and lack of processing of specific scene cues (as indicated by reduced saccadic number and greater peak of saccadic velocity). Also, in this particular virtual context, riding behaviour was linked to the degree to which the rider felt situational awareness and control in a road environment (Boer, 2005), which can be quantified with behavioural, subjective, psychophysiological and eye movement measures.

One limitation of the present work is that participants have had a limited experience on the simulator, as only a limited skill can be developed when practice is limited to 2 days. Nevertheless, as suggested by Groeger (2000), see also Groeger and Clegg (2007), the amount of practice is important for the acquisition of driving skills, so that other differences will be observed when participants have longer training and feedback on their performance. In fact, we are currently studying a brain electrical activity index for discriminating between risky and non-risky behaviours, and manipulating the amount of practice. However, we think that our results are interesting because in daily life people often ride with little riding experience. Furthermore, we controlled for bicycle riding expertise, experience with computer games, gender and age. None of these factors could account for risk-proneness or subjective or eye movement variability. Consequently, we feel that our data can be useful for understanding the risk behaviour of novel riders. However, given that we cannot completely exclude the possibility that the riders exhibiting more risky behaviours were also the most inexperienced riders, we are currently working on other lines of investigation.

Our research provides a clear contribution to the study of novice–expert (Crundall & Underwood, 1998; Underwood et al., 2002) or trained–untrained drivers (Chapman, Underwood, & Roberts, 2002) in the driving/riding context, because we concentrated in naïve riders. In contrast with other studies, one strength of our study is the use of a multidimensional methodology, using classical measures (i.e., eye fixation), measures of saccadic dynamics (such as peak of saccadic velocity) and subjective measures. Our results support those of earlier researchers but also show that the risk behaviour of untrained motorcycle riders could be explained by either a limitation of mental resources or an inadequate mental model of the situation’s potential hazards.

The performance of the high-risk group did not appear to improve with increasing experience on the simulator, suggesting that their ability to acquire information about the situation was inadequate. On the contrary to the low-risk group, had not changed performance at the end of the simulation. The decrease of high-risk group could be attributed to an inappropriate visual search strategy that will produce an increase in mental workload. Considering this and the saccadic eye response results, we suggest that the high-risk group, in contrast with the low-risk one, had either superficial or inadequate information visualisation processing or an inability for improve their performance with experience.

The complexity of the situation appears to be the key factor. When complexity increased, the visual strategy became superficial, probably as a consequence of frustration and increased effort necessitated by a lack of conscious awareness and identification of specific scene cues. We think that the shorter duration of saccades combined with a lower number of saccadic movements and higher peak of saccadic velocity seen in the high-risk group reflected their reduced appreciation of the riding situation.

In summary, the multidimensional methodology used here provides useful information about the factors leading to risk behaviour. Eye dynamic measures combined with subjective and performance data permit us to conclude that the visual searching strategy and the situation awareness of riders can be important factors in riding/driving accidents and fatalities.

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CHAPTER III

Applying the Saccadic Bin Analysis in well controlled ecological tasks

Approximation of on-line mental workload index in ATC simulated multitasks

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Applying the Saccadic Bin Analysis in well controlled ecological tasks

Approximation of on-line mental workload index in ATC simulated multitasks

ABSTRACT

Neuroergonomics can provide on-line methods suitable for evaluation of mental workload while an operator is sitting in the workplace. Participants interacted with a modified version of ATC simulated tasks requiring different levels of cognitive resources. Changes in mental workload between the levels were evaluated multidimensionally using a subjective rating, performance in a secondary task, and other behavioural indices. Saccadic movements were measured using a video-based eye tracking system. The Wickens multiple resource model was used as a theoretical reference framework. A coherent data pattern was observed. Saccadic peak velocity decreased with increasing cognitive load, in agreement with subjective test scores and performance data. In agreement with previous reports, we demonstrated that saccadic peak velocity is sensitive to variations in mental workload during ecologically valid tasks. Based on these findings, we suggest that saccadic peak velocity could be a useful diagnostic indicator for assessment of operator mental workload and attentional state in hazardous environments.

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1. INTRODUCTION

"Controller workload is likely to remain the single greatest functional limitation on the capacity of the ATM system" (Eurocontrol, 2004, p. 1). Evolution of air traffic management (ATM) in the 20th century led to changes in the role of the air traffic controller (ATC) (Kronenberg, 2005) but the most important issue is still assessment of the mental workload of tower control operators. Mental workload is defined as a "composite brain state or set of states that mediates human performance of perceptual, cognitive, and motor tasks" (Parasuraman & Caggiano, 2002, p. 17) and is considered the limiting factor regarding ATM expansion (Wickens et al., 1997). Since the 1950s, when the narrow relation between mental workload, air navigation flow and safety was discovered, this became a key issue for air navigation (Villena, et al., 2008).

The most popular eye-movement indices currently used to map mental workload components in ATC operation are pupil diameter and blinking rate (Ahlstrom & Friedman-Berg, 2006). However, there are some problems related to these indices that make them difficult to use in the dynamic and complex tasks encountered in real workplaces (Di Stasi, et al., submitted).

In this paper, we explore a relatively new alternative to previous indices of mental workload: the variability of main sequence. The relationships between the amplitude, peak velocity (PV) and duration of saccadic eye movements are often described as the main sequence (Bahill et al., 1975). There is evidence of variations in PV depending on the resources required to perform different tasks (App & Debus, 1998). These variations can be independent of amplitude. Recent findings (LeDuc et al., 2005; Di Stasi et al., 2009, 2010) have demonstrated that mental workload and/or fatigue affect the dynamics of saccades and that PV could be an appropriate measure of this relationship. Here we report further results supporting the idea that PV represents an alternative measure for assessing mental workload in complex environments.

The aim of this study was to improve on previous research using a setting in which subjects completed different ATC tasks with different complexity levels. The purpose was to explore the sensitivity of the saccadic main sequence, particularly PV, to changes in the operator's mental workload.

2. METHODS

2.1. PARTICIPANTS

Twenty-three volunteers (9 males) took part in this experiment; their mean age was 24.6 years (SD 3.65). None of the participants had ATC experience. All subjects had normal or corrected-to-normal vision and signed a consent form that informed them of the risks of the study and the treatment of personal data. They received a course credit for participating in the study. The study was conducted in conformity with the Declaration of Helsinki.

2.2. STIMULI AND INSTRUMENTS

Eye movements were sampled monocularly at 500 Hz using an Eyelink II head-mounted eye tracking system (SR Research, Ontario, Canada). Spatial accuracy was always better than 0.5°. Saccades and fixations were measured using the saccade detection algorithm supplied by SR Research. Saccades were identified by deflections in eye position in excess of 0.1° with a minimum velocity of 30 s^{-1} and a minimum acceleration of 8000 s^{-2}, maintained for at least 4 msec. A 13-point calibration and validation was performed before the start of each block (see the procedure section for block definition). Saccades around blinks, as well as fixations and saccades of less than 100 msec and 10 msec in duration, respectively, were not considered in the analysis. A headspot chin rest was used.

Participants were tested on different simulated ATC tasks. The tasks were simplified versions of real ATC operational tasks, but retained the main artifacts and interaction sequences that the ATCs have to cope with in their complex environments (Cox et al., 2007). Fig. 1 shows the trial structure and procedure. The visible airspace matrix consisted of five green nodes presented on a black background. The distance between adjacent nodes was 1.5 cm (on a Dell 21-in. screen with resolution of 1024×768 pixels). Aircraft were always located on a visible node within the matrix and could appear on any of the five adjacent nodes. For each node, eight positions were chosen at which aircraft could be shown (clockwise: up, 45°, 90°, 135°, 180°, 225°, 270°, 315°). In total, 40 different stimuli were built and each one was randomly presented twice. Images were the same in the three blocks and only the order was randomized. Aircraft position was updated every 1.5 s, within which time the aircraft would be presented to one of the four adjacent nodes. Aircraft were represented visually by their call sign (3 digits). Forty-digit call signs were extracted from a random number table. Call signs were presented in Calibri font, point size 11. Aircraft color was constant and subtended a visual angle of 1°.

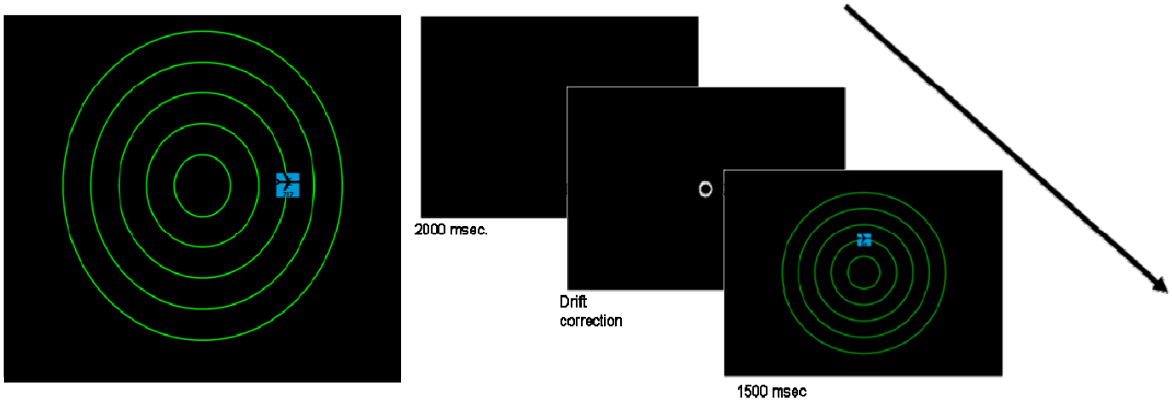

Figure 1. Sample screenshot taken from the experimental environment.

2.3. DESIGN

In this experiment three different levels of task complexity (low, medium and high) were created by manipulating the number of simultaneous tasks. The number of simultaneous task was assumed to affect the information processing load (Wickens, 2002). Low task complexity was defined as a monitoring/decision task. Medium task complexity involved a low-complexity task and a digit code task. In the high task complexity condition, the task was a combination of low- and medium-complexity tasks and a mathematical operation (paper and pencil) secondary task. All subjects started with the low task complexity and progressed through the same order.

We used a multiple-measures approach to evaluate the effectiveness of our mental workload manipulation. First, the Mental Workload Test (MWT) developed by the Cognitive Ergonomics Group was used to estimate subjective mental workload. The tool consists of 13 scales (Di Stasi et al., 2009). Second, the number of errors and delayed answers in relation to the monitoring/decision task for each complexity level was analyzed.

To estimate possible effects of changes in mental workload on eye movement indices, we analyzed saccadic amplitude (degree of visual angle), saccadic duration (milliseconds), saccadic velocity (degree of visual angle/second) and PV (degree of visual angle/second). Eye movement data were analyzed using median values to exclude the effect of noisy data (Sheskin, 2004).

2.4. PROCEDURE

Participants were tested in a quiet room and sat approximately 60 cm from the display screen. The trial consisted of one practice session and three experimental blocks. During the first practice session, 80 stimuli (the same as for experimental blocks) were presented to provide an idea of the type of stimuli and presentation times (no answers were required).

After the practice session was completed, the eye tracking system was set up and calibrated. Next, participants performed three experimental blocks, each lasting 10 min. All subjects had to complete the MWT after each experimental block.

The first of the three experimental blocks involved a decision task using a PC mouse, for which the two buttons were the answer keys. Instructions given to subjects were to decide (and answer with the mouse) whether the position of the aircraft on the screen was “critical” or “not critical”. A critical position was defined as an aircraft on one of the two smallest nodes (diameter of 3° and 6°). Participants were informed that a critical position arose from supposed proximity to the airport and priority in needing assistance. If the aircraft appeared in one of the three largest circles (diameter of 9°, 12° and 15°), its position had to be judged as not critical. Participants were requested to perform the task with their non-writing hand so that they could continue to do this with the same hand in subsequent blocks.

In the second block, a paper-and-pencil task had to be performed along with the decision task. After having located the aircraft on the screen and decided on the criticality of its position, participants had to write down the call sign (3 digits) on the sheet provided. It should be noted that in this block, as in the following one, subjects had information about the duration of the block, since the answer sheet presented 80 empty cells to be filled in.

In the last block a further paper-and-pencil task was added. As well as the tasks in the previous block, participants had to carry out a simple mathematical operation in relation to the call sign written on the answer sheet. In this last block, a 3-digit number was presented beside each empty cell for recording the call sign number, and subjects had to indicate if the number they reported was greater than (>) or less than (<) the printed number. The numbers printed on the answer sheet were constructed by adding 5 to each number chosen for the test. Trials were randomized within the block to ensure the absence of any regularity between presented and printed numbers.

3. RESULTS

In the first step we examined the effectiveness of the mental workload manipulation by analyzing MWT scores and the number of errors and delayed answers in the main task (decision task).

MWT scores were submitted to a 3 (task complexity: low, medium and high) x 13 (scales of the MWT) repeated measures analysis of variance. Significant main effects were obtained for task complexity, [$F(2, 44) = 25.069$, $p < 0.001$, MSE = 383.32; $\eta^2 = 0.5326$, statistical power = 1], (see table 1), MWT scale, $F(12, 264) = 32.842$, $p < 0.001$, MSE = 856, $\eta^2 = 0.5988$, statistical power = 1] and the interaction of task complexity and MWT, $F(24, 528) = 2.282$, $p < 0.001$ MSE = 117, $\eta^2 = 0.0939$, statistical power = 0.999). Planned comparisons revealed significant differences in MWT mean scores between all levels of task complexity (all $p < 0.0001$). These results confirm that the subjective experienced mental workload changed according to the experimental manipulation.

The Number of errors in the decision task for each subject and each task complexity condition were analyzed using repeated measures ANOVA, with task complexity as repeated factor. As expected, we obtained reliable difference in relation to the number of errors between the three complexity levels [$F(2, 44) = 8.5447$, $p < 0.001$, MSE = 3.645]. Planned comparisons of means revealed significant differences on number of errors between low task complexity and medium/high task complexity ($p < 0.03$, see table 1). Similarly, the number of delayed answers was computed and statistically tested. Results show a significant increase of the number of delayed answers with the increase of the task complexity [$F(2, 44) = 4.2751$, $p = 0.02011$, MSE = 46.710]. Planned comparisons of means revealed significant differences on number of delayed answers between low/medium task complexity and high task complexity ($p < 0.05$, see table 1).

In the next step we analyzed the sensitivity of saccadic main sequence parameters in relation to changes in mental workload. Amplitudes of the saccades were categorized into 5 bins (henceforth saccade length), ranging from 0.001º to 7.5º (0 .001° < Bin 1 < 1.5º, 1.5º < Bin 2 < 3.0º, 3.0º < Bin 3 < 4.5º , 4.5º < Bin 4 < 6.0º , 6.0º < Bin 5 < 7.5º). Three repeated measures 3 (task complexity) x 5 (saccade length) ANOVAs were calculated on the medians of saccadic duration, velocities and PV, respectively. Analysis on eye movements was carried out on 22 participants: one subject was removed due to missing data.

Analysis of the duration of saccades revealed a significant main effect of saccade length [$F(4, 84) = 735.37$, $p < 0.0001$, MSE = 8.063, $\eta^2 = 0.9722$; statistical power = 1] but not of task complexity [$F(2, 42) = 1.297$, $p > 0.05$, MSE = 5.130, $\eta^2 = 0.0581$, statistical power = 0.265]. The interaction revealed a significant effect [$F(8, 168) = 3.0793$, $p < 0.01$, MSE = 3.962, $\eta^2 = 0.1278$, statistical power = 0.9].

Similar results were observed for the mean velocity of saccades. The analysis revealed significant effects of saccade length [$F(4, 84)= 1379.5$, $p < 0.0001$; MSE = 100.404, $\eta^2 = 0.9850$; statistical power =1] but not of task complexity [$F(2, 42) = 1.6541$, $p > 0.05$, MSE = 52.0055, $\eta^2 = 0.073$, statistical power = 0.3292]. The interaction revealed a significant effect [$F(8, 168) = 2.3030$, $p < 0.05$, MSE = 37.6396, $\eta^2 = 0.09882$, statistical power = .86992].

Analysis for the PV showed main effects of saccade length [$F(4, 84) = 657.71$, $p < 0.001$, MSE = 924.0560, $\eta^2 = 0.969$; statistical power = 1] and of task complexity [$F(2, 42) = 3.396$, $p < 0.05$, MSE= 367.390, $\eta^2 = 0.1392$; statistical power = 0.608], but no interaction was found [$F(8, 168) = 1.289$, $p > 0.05$, MSE= 172.854, $\eta^2 = 0.0575$, statistical power = 0.577]. Planned comparisons of means revealed significant differences between low vs. high level of task complexity factor [$F(1, 21) = 6.186$, $p < 0.05$, MSE = 401.7502] .

Table 1. Overview of the experimental results (* p < 0.05). For MWT scores, error and delayed answer mean values were considered. Median values were considered for mean sequence parameters.

	Low Complexity	Medium Complexity	High Complexity
*MWT	36.18	41.96	47.53
*Error (number)	3.17	1.56	0.91
*Delayed answers (number)	2.00	5.39	7.87
Saccadic Duration (ms)	30.25	29.76	30.03
Saccadic Mean Velocity (º/s)	112.52	113.80	112.09
*Saccadic Peak Velocity (º/s)	215.88	212.15	209.16

As expected, for all main sequence indices, longer duration and higher velocity and PV were found with increasing saccade length (the main sequence rule). The interaction effect between saccade length and task complexity on duration and saccadic velocity revealed the influence of task complexity (the independent variable) on the main sequence elements; this became clearer in the PV analysis (Figure 2). This can be explained considering the nature of these three parameters. When a saccadic movement starts, it has an initial velocity and then accelerates. The PV is the point at which acceleration stops. It is independent of saccade duration since it is not linked to it, a priori, by a mathematical definition, such as velocity, and is independent of the distance at which saccades terminate, whereas the apparent duration of saccades depends on this

(Becker, 1989). Considering that the range for saccade length is relatively narrow (0.001º–7.5°) it is possible that the mathematical relation between these parameters could mask the effect of our main manipulation.

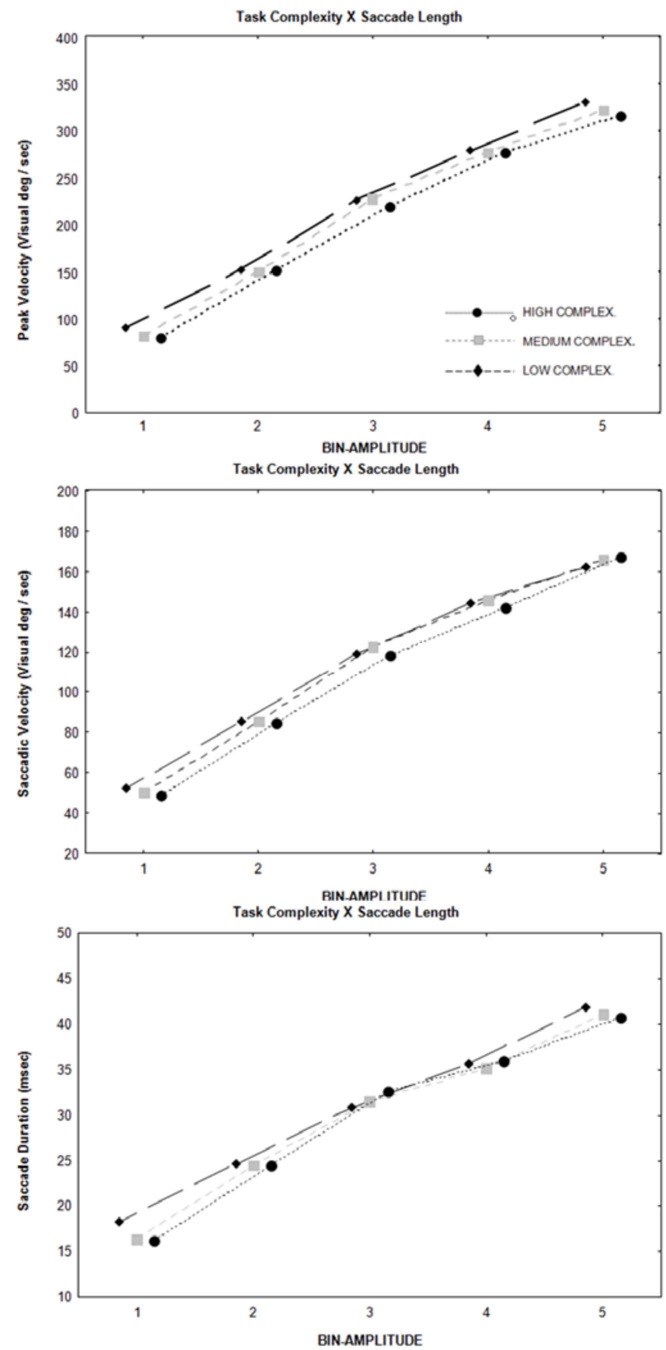

Figure 2. Illustration of the interaction between task complexity and bin-amplitude factors on the main sequence parameters. Top: Relation between saccade peak velocity and magnitude.. Middle: Relation between saccade mean velocity and magnitude. Bottom: Relation between saccade duration and magnitude.

4. DISCUSSIONS

In an information technology society, changes in mental workload can have significant impacts on operator performance, possibly leading to delays in information processing or even causing operators to ignore incoming information (Ryu & Myung, 2005). Consequently, there is a need to monitor operator functional states in real time to determine the type and level of automated assistance most appropriate in helping operators to complete tasks (Langan-Fox et al., 2009). Development of a method able to detect operator attentional states in real time during interactions with complex and dynamic systems could be a good starting point for this critical issue.

In the current investigation we produced different levels of mental workload in a complex, ecologically valid environment. Results obtained from the subjective ratings (MWT) confirmed that combining different task complexities can be useful in inducing different mental workload levels. As expected, after three sessions, behavioural measures revealed correct manipulation of task complexity as the main independent variable. The number of errors showed a learning effect for the basic task (decision task) and decreased with increasing task complexity, whereas the number of delayed answers increased in parallel with the task complexity owing to an increase in time pressure (the time to perform the task was constant during all three experimental blocks). Results obtained from the subjective ratings (MWT) and behavioural measures (number of errors and delayed answers) confirmed that combining these types of secondary tasks with task complexity manipulation can be a fruitful strategy for inducing different mental workload levels (Wickens, 2002).

On the basis of these confirmations, we investigated all parameters of the saccadic main sequence (duration, mean velocity and PV) with respect to mental workload levels. We found an effect of task complexity for PV only. Based on these findings, we suggest that saccadic peak velocity could be a useful general indicator for assessment of operator mental workload and attentional state in highly dynamic environments (Di Stasi et al., 2009, 2010).

The current work could be a starting point for further research on understanding how variations in cognitive processing and mental workload can be used to build a model to manage the dynamic allocation of tasks between human operators and support systems (Crévits et al., 2002).

Our research is relevant to a variety of domains ranging from ATC towers to call centers. For example, using real-time main sequence measures, neuroergonomists could better evaluate when an operator’s attentional state is changing (mental under/overload), helping in the design of systems able to allocate tasks in a dynamic way between the operator and the machine.

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CHAPTER IV

Applying the Saccadic Bin Analysis in well controlled ecological tasks

Main Sequence: An index for detecting mental workload variation in complex tasks

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ABSTRACT

The primary aim of this study was to validate the saccadic main sequence, in particular the peak velocity [PV], as an alternative psychophysiological measure of Mental Workload [MW]. Taking the Wickens' multiple resource model as the theoretical framework of reference, an experiment was conducted using the Firechief® microworld. MW was manipulated by changing the task complexity and the amount of training. There were significant effects on PV from both factors. These results provide additional empirical support for the sensitivity of PV to discriminate MW variation on visual-dynamic complex tasks. These findings and other recent results on PV could provide important information for the development of a new vigilance screening tool for the prevention of accidents in several fields of applied ergonomics.

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1. INTRODUCTION

In cognitive psychology and cognitive ergonomics, the theoretical construct known as mental workload (Moray 1979; Wickens, 2008) has been used to explain how humans face increasing cognitive demands associated with increased task complexity in operations where cognitive skills are more important than physical ones (Cacciabue, 2004; Boksem & Tops, 2008). Even if task complexity (defined as a function of objective task characteristics) is one of the most essential factors affecting performance, most frequently, mental workload [MW] (or cognitive load*) is the term used to describe the mental cost of accomplishing task demands (Wickens 1984; 2002; 2008). Fluctuations of attentional state are also modulated by cognitive load (Tomasi et al., 2007), i.e. the allocation of mental resources (attention) is hinged to different levels of MW (Wickens & Hollands, 2000) and it has been shown that an increase of cognitive load involves increased attentional processing (Tomasi et al., 2007).

The multiple resources model developed by Wickens (1984; 2008) is a theoretical framework for workload assessment related to human information processing. The model provides an explanation for mental activity changes that follow after changes of the operational conditions (e.g. task difficulty, time pressure, etc.). According to the Wickens' model, attentional resources can be categorized along three dimensions: (a) input/output modalities, (b) processing codes, and (c) response execution. Accordingly, high similarity in the resource demands imposed by the task components leads to severe competition for similar resources which results in a high level of workload. This could be the case, for example, due to high demands of perceptual or working memory processing.

The development of techniques for measuring MW has been a fundamental research topic in psychology and applied ergonomics over the last three decades. In order to estimate alternative solutions to a system design, it is not only necessary to focus on the output supplied by the system, but also on the workload experienced by the operator. Consequently, the ability to continually measure MW correctly is closely related to measuring performance in safety-critical context (Gould et al., 2009), improving the usability of the human–computer interface (Casner, 2009), and designing appropriate and adaptive strategies for automation (Jou et al., 2009; Cacciabue & Carsten, 2010). Unfortunately, MW cannot be measured directly, but must be estimated indirectly by measuring variables considered to be related to it. Therefore, we are presently exploring

*Although the terms 'mental workload' and 'cognitive load' are used interchangeably, they are not identical (for a discussion, see Sweller et al. 1998). Nevertheless, for the purposes of this paper we will use the expressions as synonyms.

the saccadic main sequence as an alternative measure to the classical psychophysiological measures (i.e. heart rate, electrodermal activity or electroencephalographic activity, see Parasuraman, & Rizzo, 2007) to assess mental state.

1.1. MAIN SEQUENCE AND MENTAL WORKLOAD

Cerebral activity measurements, such as functional magnetic resonance imaging or electroencephalography provide an opportunity for a more direct and sensitive assessment of mental workload (Ryu & Myung, 2005). The human eyes are outgrowths of the brain and are considered as part of the central nervous system (Hoar, 1982; Wilson & O'Donnell, 1988). For this reason, the analysis of gaze parameters may serve as a good index of mental state. The speed of saccadic movements, for example, not being under voluntary control (Leigh & Zee, 1999), could be directly sensitive to the effects of variations in mental state, as they cannot be affected by the persons' motivational state (Rowland et al., 2005). In the literature, eye movement parameters have already been used as indicators of attentional sate (see for example: Ahlstrom & Friedman-Berg, 2006; Schleicher et al., 2008; Dey & Mann; 2010). However, researchers have often focused on the relationship between saccadic amplitude and fixation duration more than on saccade dynamics (for example: Unema et al., 2005; Graupner et al., 2007; Pannasch et al., 2009).

Saccadic eye movements vary in amplitude, duration, and peak velocity (Dodge & Cline, 1901; Dodge, 1917). The relationship between these three parameters has been called the 'main sequence', to indicate that PV and saccadic duration increase systematically with the amplitude (Bahill et al., 1975). It is of importance for the purpose of the current study that the PV is independent of the saccadic duration since it is not linked to it, a priori, by a mathematical definition, like saccadic velocity is (Becker, 1989). Recent studies in our laboratory have focused on analyzing the influence of particular mental state (i.e. mental overload) on the main sequence, finding an inverse relationship between the increase of MW and PV values (Di Stasi et al., 2009; Di Stasi et al., 2010 b; Di Stasi et al., 2010 c).

Di Stasi et al. (2009) evaluated whether measures of eye activity correlated with MW and different types of risky behaviour using a riding simulation task. It was found that the high-risk group had shorter saccade durations and higher PV's than the low-risk group. On the Mental Workload Test [MWT, see below] the high-risk group scored significantly higher on several dimensions. Furthermore, PV showed several significant correlations with MWT dimensions. The negative correlations of PV and subjective scales of MW suggested that, given a high level of risk proneness, lower PV was associated with a higher level of subjective workload.

In another investigation, Di Stasi et al. (2010 c) reported an experimental study in which participants drove through three virtual simulations with each simulation demanding different amounts of cognitive resources. In this study, the authors manipulated traffic density and the presence of a secondary task, to create three levels of task complexity (low, medium and high). Lower PV coincided with subjective test scores (MWT) and performance data in showing a higher MW for the high density traffic condition combined with a secondary reaction time task.

Finally, simulating a multitasking performance in air traffic control setting, Di Stasi et al. (2010 b) studied the relation between the main sequence parameters and task load. The created tasks demanded different perceptual and central processing resources, as well as response resources. Results obtained from the subjective ratings (MWT) and behavioural measures (number of errors and delayed answers) confirmed that MW levels varied according to task demand. These different levels of MW were reflected in PV values. The authors found that there was a reduction in PV when task complexity assessed by MWT increased and performance also decreased.

The aforementioned experiments are quite similar. Without considering the experimental context and psychophysiological measuring instrument (Eye Link systems, SR-Research at 500 Hz), all considered the PV as the third element of the main sequence, and evaluated the mental state variations multidimensionality. In the last two investigations, the authors used a common procedure to eliminate the influence of changing amplitudes on saccadic velocity. In general this procedure is called a "saccadic-bin analysis" (Di Stasi et al., 2010 a, b, c), i.e. analyzing the PV as a function of saccade length. This method of analysis could represent a different and valid approach compared to the classical standardization procedure proposed by Schleicher et al. (2008) because it is not necessary to perform any corrections on the collected data or compare the participants measured values with some normative data bases. This last point is highly relevant considering the elevated intersubject/intrasubject variability of main sequence parameters (Bahill et al., 1981).

Overall, studies point to the conclusion that the level of MW could be reflected by changes in PV. This is in line with the explanation based on an 'energy function' provided by App and Debus (1998). According to these authors, PV varies with changes in resources required to perform the task. App and Debus (1998) explained this effect using the cognitive-energetical performance model of Sanders (1983), which presumes an influence from factors related to energy regulation, such as the energy demands of the task. Furthermore, App and Debus (1998) suggested that saccadic velocity has not been considered as an index of mental state because it is strongly dependent on saccadic amplitude and orbitary direction and is frequently uncontrolled in real-life contexts. This is contrary to Bahill and Stark (1975) who conclude that the saccadic eye movement system provides great potential for psychologist and human factors engineers as an indicator of general psychological state of people performing real tasks. Unfortunately Bahill and Starks' suggestion has not been considered at all to date (Parasuraman & Rizzo 2007, Schleicher et al., 2008).

Because of this, in the present study, we aim at extending previous research by using a more controlled setting in which participants performed a dynamic task with the FireChief incident simulator (Omodei & Wearing, 1995). The purpose was to explore the sensitivity of the saccadic main sequence, particularly PV, to changes in the participant's mental state. Our working hypothesis was that MW would affect PV, showing a decrement in its values for higher task complexity. We also expected that participants would learn and thus their performance would improve. Since learning is associated with a reduction in the cognitive resources needed to perform the task (Cañas et al., 2005), we also expected an affect of learning on PV that would reflect a reduction of MW (increase of PV values).

2. METHODS

2.1. PARTICIPANTS

Forty-six Granada University undergraduates (age 18–36 years) participated in the experiment for course credit. All subjects had normal vision and were naïve to the hypothesis being investigated and had never participated in previous eye movement experiments. Their familiarity with PC-based games was very low. The allocation of the subjects to each group was random, except for the gender variable, which was balanced. The study conformed to the declaration of Helsinki.

2.2. MENTAL WORKLOAD TEST [MWT]

The MWT was adapted by the Cognitive Ergonomics Group (Cronbach's alpha 0.68; Fajardo, 2001) from two pre-existing instruments, the NASA-TLX (Hart & Staveland, 1988) and the Workload Profile (Tsang & Velazquez, 1996). The instrument asked participants to make an evaluation of 13 factors. Each factor was presented as a visual analogue scale with a title and a bipolar visual scale [low/high at each end]. Numerical values were not displayed to the participants, but values ranging from 0 to 100 (twenty-one points) are assigned to positions on the scale during data analysis (for more details see Fajardo, 2001; Di Stasi et al., 2009).

2.3. EYE TRACKER RECORDING

Eye movements were recorded with the EyeLink II head-mounted system (SR Research, Ontario, Canada) with an accuracy of better than 0.5° and a 500 Hz sampling rate. Fixation onset was detected and transmitted to the presentation system with a delay of approximately 12 ms. A 13-point calibration and validation was performed before the start of the each experimental session. Saccades and fixations were found using the saccade detection algorithm supplied by SR Research; saccades were identified by deflections in eye position in excess of 0.1º, with a minimum velocity of 30ºs-1 and a minimum acceleration of 8000ºs-2, maintained for at least 4 ms. Fixations around blinks, as well as fixations and saccades with durations less than 100 ms and 10 ms, respectively, were not considered in the analysis. The median values of saccadic amplitude and PV were considered in the analysis.

2.4. TASK

In the following experiment, we used the microworld FireChief (Omodei & Wearing, 1995). Microworlds are problem-solving tasks that reflect the appropriate research environment to test our hypothesis. Microworlds are computer-generated artificial environments that are complex (have a goal structure), dynamic (operate in real time), and opaque (the operator must make inferences about the system) (Brehmer & Dorner, 1993). FireChief simulates a spreading forest fire paradigm, forcing the subject to continuously track a complex visual situation to make decisions. The task was to extinguish the fire as soon as possible. In order to do so, participants could use helicopters and trucks which could be controlled by mouse movements and keyboard presses. In our experiment, two commands were used to control the movement and functions of the vehicles: (1) drop water on the current landscape segment, and (2) start a control fire (trucks only) on the current landscape segment. Consequently, participants were allowed to move vehicles, drop water, and start control fires. Commands were given using a 'drag-and-drop' approach by first selecting the desired vehicle (by moving the mouse cursor into the landscape segment containing it) then pressing a key on the keyboard. Every time a participant performed an action, it was saved in a log file as a row containing an action number, the command (e.g. drop water or move) or event (e.g., a wind change or a new fire), current performance score, vehicle number, vehicle type, position, and landscape type. Fire intensity and speed of spread depended on the wind direction.

Different cells in the screen had different flammability ratings and values (houses were more valuable than forests, for example). The participant's mission was to save as much forest as possible, to preserve the most valuable cells, and to prevent the trucks from being burnt. Participants began with a score of 100 and gradually lost points; for example, for every house destroyed, 15 points were subtracted (every element had a specific point value). Participants could see a window with their overall performance score at the end of a trial, which was calculated by subtracting the value of the burnt trucks and cells.

2.4.1. SCREEN CONFIGURATIONS PROCESS (PRE-EXPERIMENTS)

To establish that PV is affected by MW, it is necessary to use an external verified task that varies MW. To reach this aim, the selected screen configurations of FireChief (low/high demanding see below) have been created after performing two pre-experiments, following the preliminary results of Fajardo (2001), in which the author developed a subjective instrument to assess MW while testing different visual screen characteristics.

As a first step to the creation of the final screen configurations, we needed to determine the physical characteristics (color, position, and grouping) of the elements present on the screen. The screens simulated a spreading forest fire. The elements of the forest were pastures, trees, animals, houses, fire focuses, helicopters, and trucks. Each element contributed to the visual complexity of the screens but subjects were asked to focus on three central elements: fire focuses, helicopters, and trucks, which were manipulated and named target elements. The rest of the elements remained constant and were named background elements.

Three variables were manipulated: Eccentricity, Grouping, and Color. The Eccentricity of the target elements could be at the edges or in the centre of the screen. Each target could be located in a separate place on the screen or be grouped by type (trucks, helicopters, fire focuses), which determined the Grouping of the elements. The Color of each target could be at four levels: brown (color shared with the background elements), red, pink, and the default colors provided by the software

The combination of these three dimensions resulted in 16 configuration conditions for which ten screens were built, that is, a total of 160 different screens. The difficulty each condition was evaluated using the mean time of a visual search and count task in a separate study. Twenty-four participants (different set of experimental volunteers) were asked, 'Are there seven target elements in the screen?' They had to search and count the target elements (trucks, helicopters, and fire focuses) for each of the 160 screens created. Participants produced slower response times in the Edge/Grouped/Default condition ($M = 5480$ msec , $SD = 1964$) and faster response times in the Centre/Grouped/Brown condition ($M = 4157$ msec, $SD = 1569$), $F(1, 23) = 27.18$; $MSe = 1628461$; $p < 0.001$.

Then ten Firechief screens from each configuration condition were used to create two different set of screen stimuli: High (Edge/Grouped/Default condition) and Low (Centre/Grouped/Brown condition) task demanding. To test the effects of the different screen configurations on MW, we ran a second pre-experiment with 35 participants (different set of volunteers). Participants were divided in two groups and performed an experimental session, working to extinguish the fires during two trials (the same used in this study). Group A (18 participants) performed the task with the high demanding screen configurations and group B (17 participants) with the low demanding ones. At the end of the session, participants filled out the MWT. Group A scored higher on the perceptual/central dimension of the test than Group B, $F(1, 33) = 6.17$, $MSe = 352.612$, $p < 0.01$. From these results (reaction time and perceived task difficulty) we could assume that the manipulated factors (Eccentricity, Grouping, and Color) affect the subjective MW. Figure 1 shows the final screen configurations selected for our experiment.

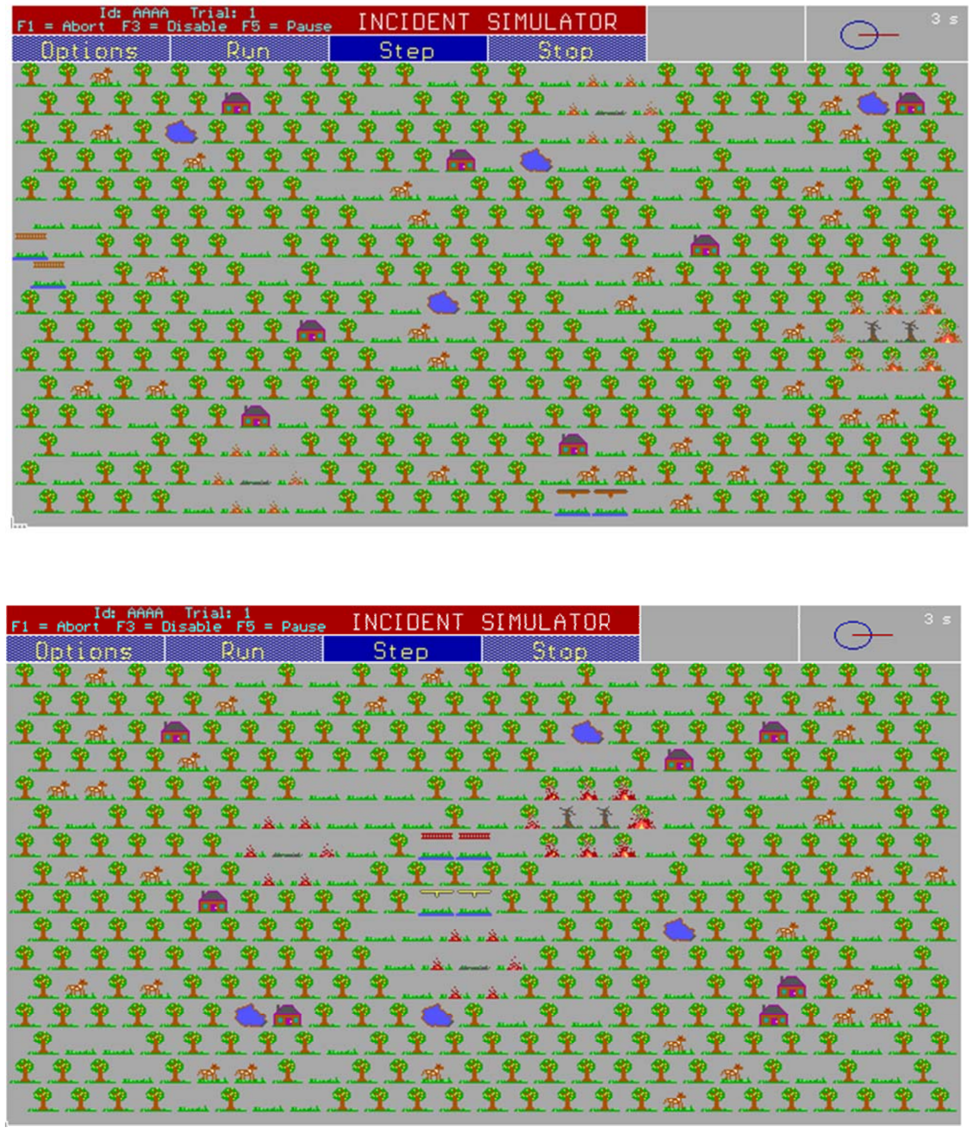

Figure 1. Screen Configuration (top: high demanding, bottom: low demanding). For more details about the elements present on the screen see Cañas et al., 2003.

2.5. PROCEDURE

At the beginning of the experimental session, participants received a general description of the structure of the experiment and were given an instruction sheet. During a short briefing, participants were informed that in the first and last simulations their ocular movements would be monitored and recorded and each participant read and signed the informed consent form. After a training session (three simulations of 200 seconds each), during which the experimenter checked (supervising the interaction behaviour with the microworld) that participants understood the system control and usage, the experiments started. At the end of the training and before the last trial, the experimenter calibrated the eye tracker.

Participants performed ten trials (the first and the tenth with the headband on and recording eye movements) in one consecutive session. At the end of the first and tenth experimental trial, participants compiled the workload test, still with the headband on. Each simulation ran for 260 seconds and the study session ended after approximately 1 hour and 30 minutes.

2.6. DESIGN

The experiment followed a 2 x (2) mixed factorial design, with Screen Configuration as a between-participants variable (Low vs. High demanding), and Training (1^{st} vs. 10^{th} Trial) as a within-participants variable. Psychophysiological and subjective indices were sampled during the first and tenth simulations. This decision was made for two main reasons: first, filling out the questionnaire after each trial could interfere with our main manipulations; second, even though the eye tracker was lightweight, we preferred the participants not wear the head-mounted system for the entire duration of the experiment, to avoid any confounding factor (like distress or discomfort). The dependent variables were the performance score (calculated automatically by the FireChief software), main sequence parameters (PV and saccadic amplitude), and scores in the subjective MWT.

3. RESULTS

3.1. SUBJECTIVE INDICES

The mean scores of the MWT scales were submitted to a 2 (Screen Configuration, between subjects) X 2 Training (1st versus 10th Trial, within subjects) analysis of variance (ANOVA). No significant effects were found (see Table I).

3.2. PERFORMANCE SCORES

For the performance mean scores, a 2 (Screen Configuration, between subjects) X 2 Training (1st versus 10th Trial, within subjects) ANOVA was run. Six subjects were excluded from this analysis because of log-system failures during the experimental recording. For this variable, only the factor Training was significant, $F\ (1, 38) = 50.31$, p

< 0.001, MSe = 85.5. During the last trial, participants performed better than the first one, showing the effects of the training (see Table I).

3.3. SACCADIC PEAK VELOCITY

Due to the fact that PV increases systematically with the amplitude, the saccade amplitudes were categorized into 8 bins (henceforth Saccade Length). Eight bins ranging from 0.01º to 13.9º were created (0.01° < Bin 1 < 0.9º, 0.9º < Bin 2 < 1.9º, 1.9º < Bin 3 < 3.9º , 3.9º < Bin 4 < 5.9º , 5.9º < Bin 5 < 7.9º , 7.9º < Bin 6 < 9.9º , 9.9º < Bin 7 < 11.9º , 11.9º < Bin 8 < 13.9º). Following this binning procedure (Di Stasi et al., 2010 a, b, c), the resulting medians of PV were submitted into 2 (Screen Configuration, between subjects) X 2 Training (1st vs 10th Trial, within subjects) x 8 (Saccade Length, within subjects) and the ANOVA were calculated.

The Screen Configuration factor showed a significant effect, $F (1, 44) = 4.11$, $p < 0.05$, MSe = 8769.77. Participants performing the task with the High Demanding screen had a lower PV than participants with the Low Demanding screen. The variable Training was also significant, $F (1, 44) = 5.81$, $p < 0.05$, MSe = 1777.03. PV in the last trial was lower than it was in the first trial (see table I). As hypothesized, higher PV were found with increasing saccade length $F (7, 308) = 2685.7$, $p < 0.001$, MSe = 746.15 (the main sequence rule, see figure 2). The interaction Screen Configuration x Saccade length, Training x Saccade Length, and Screen Configuration x Training x Saccade Length also revealed significant effects [$F (7, 308) = 2.21$, $p < 0.05$, Mse = 746.15; $F (7, 308) = 2.93$, $p < 0.05$ and $F (7, 308) = 2.27$, $p < 0.05$, MSe = 364.90 respectively]. We next analyzed the Screen Configuration x Training x Saccade length interaction, separating the 1st vs. 10th trials (see figure 2). Analysis of simple effect showed that in the 1st Trial, the High demanding screen had a lower PV in the 2nd , 3rd , 4th , and 8th bins [minimum value of $t = 2.03$, $p < 0.05$]. The 10th Trial showed the same effect, but only in the 3rd and 4th bin [minimum value of $t = 2.27$, $p < 0.05$].

Table I. Overview of the experimental results (mean values): psychophysiological data [saccadic peak velocity (visual deg/second)], performances scores, and subjective results. The results are organized in relation to the two experimental conditions (left: Low demanding screen configuration, right: High demanding screen configuration).

	Low Demanding Screen Configuration		High Demanding Screen Configuration	
	1st Trial	10th Trial	1st Trial	10th Trial
Saccadic Peak Velocity (º/s)	296.91	285.60	279.08	274.49
Firechief Perfomance (score)	67.7	80.3	67.9	84.6
MWT (score)	50.51	51.21	52.32	51.45

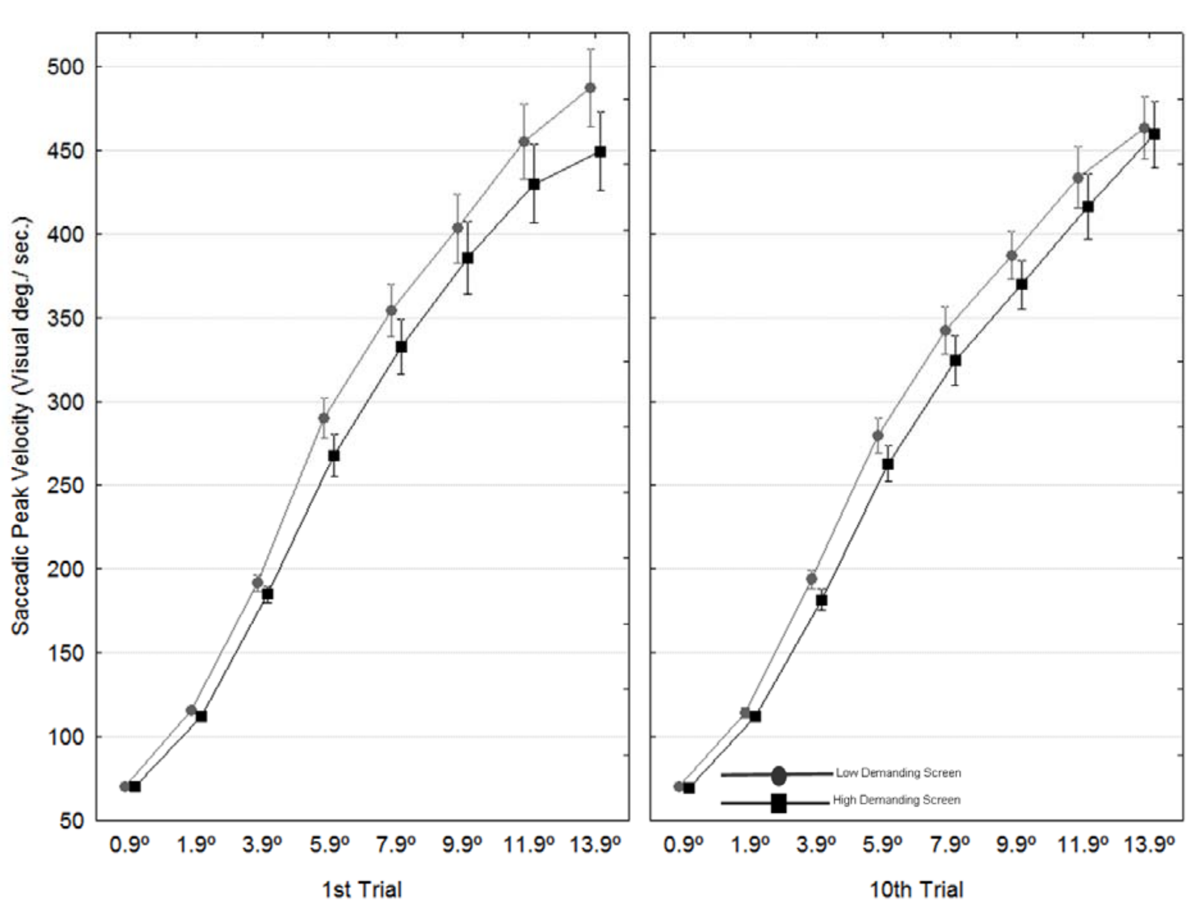

Figure 2. Illustration of the interaction between Screen Configuration x Training x Saccade length factors. Vertical bars denote 0.95 confidence intervals

4. DISCUSSION AND CONCLUSIONS

Recently, there has been a tendency in applied ergonomics to use a combination of performance, subjective, and psychophysiological measures to assess user' MW (Brookhuis et al., 2008). Whereas subjective measures offer us information about workers' perceptions of the conditions of work, performance-based and psychophysiological measures provide information about the objective conditions of the work or the tasks' requirements for specific resources. Furthermore using psychophysiological measures allows continuous evaluation of MW in real time (Miyake et al., 2009; Trimmel al., 2009).

The main aim of this experiment was to analyze the sensitivity of saccade dynamics to detect variations in MW during complex and dynamic interaction. In particular, we wanted to show the sensitivity of PV to varying degrees of MW. The experiment was set up to test the validity of PV as an alternative index of MW, comparing the results of performance and subjective ratings in response to different screen configurations and learning phases.

The effects of manipulated factors (Screen Configuration demand and Training) were not detected at all by the MWT and only in part by the performance measure. Although there could be several explanations for these results, the simplest one is that the sensitivity of these two measures for detecting variation in participants' MW was too low.

In general, these results confirmed the dissociations between questionnaires and PV (Di Stasi et al., submitted) as well as between performance and user estimates of performance and MW (Yeh & Wickens, 1988; Horrey et al., 2009).

Within the limits imposed by the task, PV was sensitive to our manipulations. Consistent with previous studies (Di Stasi et al., 2009; Di Stasi et al., 2010 b, c), we found lower values of PV associated with the higher MW condition.

As mentioned in the introduction, unlike mean velocity, PV is independent of saccadic duration because it is not a priori linked to it by a mathematical definition. Furthermore, PV is independent of thresholds definition at which saccades terminate, (Becker 1989). PV therefore appears to afford a good index of saccadic programming, because it is not solely determined by the physical features of external world, and can reflect the effects of MW on it. Neuroanatomically, the cerebral cortex and the brainstem are components of the visual-saccadic system (Munoz & Everling, 2004). Munoz and Everling (2004) explained that the frontal cortical oculomotor area (which includes the frontal eye fields, supplementary eye field, and dorsolateral prefrontal cortex) plays a central role in the top-down control of saccades, and consequently, cognitive processes must play an important role in coordinating visual processes. This reasoning makes plausible the hypothesis that if some factors, including task demands (Steinman 2003), could affect these neural circuits, it might be reflected on the saccade dynamics. In our experiment, task complexity (or MW experienced by the participants) impaired the PV (no effect was found on saccadic duration, data not shown), indicating that this "interference" on the main sequence must arise at a very late stage of the ocular motor processing, at the level of the excitatory burst neurons, which code the velocity signal of saccades with their firing rate (Zils et al. 2005). This explanation is in agreement with the circuitry diagram presented by Munoz and Everling (2004). The frontal cortex has direct excitatory connections with the reticular formation, and if this connection is affected by increased attentional processing during the high MW condition (Tomasi et al., 2007), it could modify the main sequence (in this case a decrease in PV values). This suggests that the reduced PV found in the high demanding screen condition could reflect some interference on the brainstem reticular formation activity (concretely on the synchronization of firing times).

The Training factor (or learning), affected performance as usual. The difference in performance between the first and the last simulations showed that participants developed problem-solving strategies which allowed them to reach a certain level of expertise on the task. Probably, the same performance results for both levels of task complexity were obtained because the relative ease of the task and the low sensitivity of the used behavioural measure. Interestingly, an unclear learning effect on PV has been found. As we might expect, as participants learned to perform the task, the final scores increase too, however the effect on the PV was not in the same direction. We expected a return to normal main sequences (in this case increases of PV) due to the reduction of mental effort invested to perform the simulation. In both groups we found the contrary, a general reduction of the PV values. After ten simulations, both task complexity groups obtained the same results (on six out of eight bins). The analyses for influences of Training on PV could prove that mental fatigue (more precisely of time on task) also modulates PV.

Following the explanation given for the MW effect, and in accordance to the Munoz model, the results for the time-on-task could be explained by the influence of sleep-regulating centers (i.e. caudate nucleus, thalamus, globus pallidus external, substantia nigra, and substantia nigra pars reticulate) on the same neural area (i.e. brainstem reticular formation). In the domain of saccadic eye movement research, one of the most important topics is related to the effect of sleep deprivation on saccadic behaviour and performance (for example see: LeDuc et al., 2005; Morad et al., 2009; Hirvonen et al., 2010). These researchers share the same experimental design (with some variations, such as the amount of nighttime sleepiness or the interval between battery tests), and showed a common result: a decrement of the saccadic velocity while “deactivation state” increases. Even though in our experiment we did not manipulate any variable related to sleepiness, the task requires subjects to maintain a high level of attention for approximately 1 hour which could bring them to a state of mental fatigue (Lorist et al., 2005).

For this reason we think that some mental fatigue effects can be addressed in the decrease of PV (on the 10th trial), in line with the original work of Schmidt (1979), Galley (1989), or with our latest results (Di Stasi et al., submitted). In all experiments, a reduction of PV was found with an increase of mental fatigue, the former in a controlled setting and the latter in a 2 hour virtual driving task.

To sum up, task complexity and mental fatigue have a general impairing effect on PV which is probably mediated by a different (i.e. a less synchronized) maximal firing rate of the saccadic burst neurons in the brainstem reticular formation.

There are some limitations to our study. The first is that eye movements were only recorded in the first and last trial, approximately 9 minutes in all. These results would be more convincing, if eye movement data would be available for the complete experiment. In any case, this study combined with other recent investigations on PV provide important information about the PV as an alternative mental state index. Second, no subjective ratings or alternative measures of mental fatigue were used to verify the modulation of this factor on the main sequence. This weakens our speculations, however to preserve task success (despite fatigue), it is common to find a compromise between speed and accuracy (Fitt, 1954; Missenard et al., 2009), it might be possible to discover a similar trade-off in the saccadic dynamics. For this reason, next investigations could contain a well-controlled saccade-making task in order to analyze also the accuracy of the saccade movements.

Finally, one problem with the analysis of big-saccades is that the effect of MW and mental fatigue generally becomes clear on big magnitude saccades (for example Di Stasi et al., 2010 c). While using video display terminals, the operator is screening a reduced area of interest (approximately 20º) and as a consequence generate smaller magnitude saccades (see Di Stasi et al., 2010 b). For this reason the analysis of very small saccade, including fixational eye movements (saccade < 1º), could represent an optimal alternative solution. Recently, much progress has been made in understanding the behaviour of these small saccades (called mircosaccades) during the fluctuation of attentional state, (see Martinéz-Conde et al., 2009 or Rolf, 2009 for a review). Some investigators have started to speculate more concretely about the effect of task complexity (Otero-Millan et al., 2008) and cognitive load (Laubrock et al., 2005) on microsaccade behaviour (i.e. number of microsaccade per second). Both researchers (using different paradigm' tasks: free-viewing task and attention cuing task, respectively) have shown that the microsaccade rate could be modulated by the change on task demand. On the basis of these preliminary results it could be concluded that as the cognitive demand of the task increases, there is an increase in microsaccade rate (Laubrock et al., 2005; Otero-Millan et al., 2008; but see Pastukhov & Braun (2010)).

Notwithstanding the above, these results give support to our hypotheses, and based on them, we can say that PV is a promising measure for assessing variations in cognitive demand during a dynamic, visual simulation task with different levels of complexity. They also confirmed our previous results investigating risky riding behaviour (Di Stasi et al., 2009), simulated driving performance (Di Stasi et al., 2010 c; Di Stasi et al., submitted), and air traffic controller simulated setting (Di Stasi et al., 2010 b). In line with the original results of Galley (1989; 1998) and with several modern investigations (for example Hirvoen et al., 2010), our results showed that saccadic dynamics are affected by changes in mental state, and they could be a starting point for further research to uncover how variations in cognitive processing demand and MW affect saccade dynamics during real work condition.

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CHAPTER V

Saccadic peak velocity as a driver attentional index

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

ABSTRACT

Developing a valid measurement of mental fatigue is still a big challenge and would be beneficial for various application areas, for instance to improve 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 particularly the peak velocity of saccadic eye movements is sensitive to changes in mental fatigue. Ten participants completed a fixation task before and after two hours of driving in a virtual simulation 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 was decreased after driving while the duration of saccades was 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.

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1. INTRODUCTION

The 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 & Riley, 1977). 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 & Tops, 2008). Thus, in a kind of "fallacy of automation", the total resource demands are de facto not reduced, but redistributed such that today, operators perform rather cognitive tasks, such as planning, idenitifying 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 a synonym of muscle fatigue (Lal & Craig, 2001). 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 subspecies of human functional states (Leonova, 1998). According to Lal and Craig (2001), mental fatigue is one critical factor in the 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 are already known, measuring mental fatigue—especially in complex dynamics tasks—is still a challenging task (Shen et al., 2008). Recent studies have investigated mental fatigue using behavioural data, such as eye movements (Stone et al., 2003; Schleicher et al., 2008), and psychophysiological measures, such as fMRI and EEG (Wijesuriya et al., 2007; Cook et al., 2007; Smiley, 2007). Due to the difficult and complex set up, the latter measures are less appropriate for the use in applied scenarios outside the lab. 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 the vertebrate embryonic development the eye originates as outgrowths of the brain and can therefore be considered as part of the central nervous system (Wilson and O'Donnell, 1988). Accordingly, the analysis of gaze parameters should provide optimal indices of alertness, and an easy way for 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 & Zee, 1999). Therefore, they are 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, blinking rate and pupil size (Wickens & Hollands, 2000). The latter two have often been analyzed while driving (e.g. Recarte & Nunes, 2000; Nunes & Recarte, 2002), but its utility is limited in natural environments for several reasons. Firstly, regarding the blink rate, a higher number of blinks has been reported as a function of time on task which correlates with an increased level of fatigue (e.g. Stern et al., 1994). Accordingly the eyes are closed more often resulting in increased periods of information loss. According to Velichkovsky et al. (2002a), even a normal blink rate (without indications of fatigue) results in being 'blind' for up to 4% of the time. In summary this results for an average workday of 8 hours in an information loss of approximately 20 minutes, without considering effects of fatigue. 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. Moreover, it would be a promising approach to detect indications of fatigue even before it is expressed in the blink behaviour; therefore minimizing the information blindness Secondly, analyzing the pupil size in natural environments is difficult since various factors have an influence on it, e.g. emotion and ambient lighting (Beatty & Lucero-Wagoner, 2000). Therefore, pupil size changes can hardly be attributed to particular factors. The approach we present here also focuses on eye movements, but particularly on the dynamics of saccades.

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 & 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). Moreover, the relationship between PV and amplitude seems to be more complex than has previously been assumed.

As a result of their investigation of fatigue and saccadic eye movements, Bahill, Clark and Stark (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 thirty years, this suggestion has received only little attention (Parasuraman & 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 influence 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 & Debus, 1998), alertness (Thomas & Russo, 2007), natural fluctuation of vigilance (Fafrowicz et al., 1995), sleep deprivation (Zils et al, 2005) and drug-induced sedation (Grace et al., 2010), mental workload (Di Stasi et al., 2010 b, c, submitted), 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 so that oculomotor performance is dissociated from the natural role of the saccades, which rapidly bring perceptual information to the fovea (Montagnini & Chelazzi, 2005). Previous research on saccadic behaviour has extensively made use of rather artificial fixate-and-jump paradigms, where the task is to fixate on a stimulus presented on a screen until a target appears, and then saccade to the target as fast as possible. In the antisaccade task, the saccadic movement is required in the opposite direction of the target (e.g. App & Debus, 1998; Zils et al., 2005). This research has been criticized for using an artificial task that could produce artifacts (Edelman et al. 2006).

However, the variation of saccadic dynamics as a mental fatigue index in ecological conditions, like driving for instance, has only rarely been investigated (Galley, 1993; Schleicher et al., 2008). In the work by Galley (1993), gaze and blinking behaviour were reordered during driving with different secondary tasks. Participants had to look for the presence of particular information at various positions. Results demonstrated an increased blink rate after the concurrent task was finished; the saccadic velocity was found to decrease with increasing mental fatigue (time-on-task). Galley concluded that blinking behaviour could be a good indicator of visual behaviour interruption costs (i.e. orienting the gaze from the display monitor to instrument panel for inspecting it) while saccadic velocity could represent a sensitive index of driver (de)activation. Schleicher et al. (2008) examined changes in several oculomotoric variables (including main sequence parameters and blinking behaviour) as a function of increasing sleepiness in simulated traffic situations. Participants were driving for two hours in a monotonic road circuit (no secondary task). It was found that blinking behaviour (blink duration, delay of lid reopening, blink interval and standardised lid closure speed) was a reliable indicator of objective and subjective sleepiness. Concerning saccade parameters, only saccadic duration varied as a function of sleepiness.

1.2. THE CURRENT STUDY

In the current experiment, we go beyond the previous work by (i) applying the saccadic bin analysis (Di Stasi et al., 2010 a, b, c, submitted) on eye movement data instead of the standardization procedure (Schleicher et al., 2008); (ii) examining the PV as an alternative to the saccadic mean velocity and (iii) validating the findings from on-line recorded data by comparing the results with data of a well controlled experiment, i.e. a simple fixation task; (iv) using up-to-date video-based eye-tracking in contrast to measuring EOG.

The saccadic bin analysis is assumed to be more appropriate for the purpose of this research than the standardization procedure, because no corrections on the collected data are required and individual date is not compared with normative data bases. In general, the procedure suggested by Schleicher et al., (2008) standardizes the saccadic velocity and duration values following this formula: Standardised value = 100 * (measured values / expected values for this amplitude). Moreover, it has already been demonstrated that the PV provides reliable information about a person's degree of mental activation/fatigue using the saccadic bin analysis. However, previous works about this topic have some limitations. For example, in the work presented by Di Stasi et al., (2010 b) the authors were unable to distinguish between the effects of task complexity and time-on-task, probably due to the nature of their experimental design. Presumably to avoid influences of task switching during the experimental session, the global order of task complexity variable was not balanced across the participants. In general, all results presented by Di Stasi and colleagues (Di Stasi et al., 2010 a; b; c) were obtained while participants interacted with computer-generated artificial environments, but the experimentally simulated settings were not fully controlled (for the nature of the same task: dynamic and complex, i.e. Funke, 1991). Based on these evidences we have now designed a well-controlled experiment to surmount the methodological problems encountered in the previous studies, and particularly the influence of time-on-task on the disruption of the main sequence rules—by maintaining the task complexity constant—and verifying the results obtained during driving with data recorded during a simple fixation task. Finally, video based eye-tracking represents the current state of the art, is fully remote and non-intrusive and has also been used in similar experiments.

In this study, we used a controlled fixation task to measure participants' mental fatigue induced by two hours of driving in a virtual environment. The fixation task was applied three times: before driving, after driving, and after a short rest break (without food or caffeine-based drink consumption) at the end of the session. This design was used because it is still under debate how much time of continuous driving is possible until a break is required (Nilsson et al., 1997, Ting et al., 2008). However, we followed the EU regulation (e.g. VOSA, 2009) and the recommendations of the American department of transportation for a safe driving behaviour (e.g. FMCSA, 2000) when designing the proportion between driving time and rest.

The experiment is based on the assumption that mental fatigue of our participants increases after two hours of driving in monotonous conditions. As a working hypothesis, we propose that mental fatigue will affect the saccade dynamics (disruption of the main sequence rule, reflected in a reduction of the PV for large saccades) and impair the performance in the driving task (increasing driving speed variability). Furthermore, due to the mental workload resulting from the task, we expect a stronger influence of mental fatigue on PV. We anticipate the main sequence parameters will be most sensitive to variations in the mental state of the driver.

2. METHODS

2.1. PARTICIPANTS

Ten healthy volunteers, 5 females and 5 males ranging in age from 19 to 36 years (mean age 23.9; SD 4.9) participated in this experiment. All subjects had normal or corrected-to-normal vision and were holders of a driving license (mean 5.6 years; SD 4.4). Only non-smokers were recruited and they had to abstain from alcohol 24 hours and from caffeine-based drinks 12 hours before participating. All participants slept at least 7 hours before being evaluated (mean 8.2 hours; SD 1.2), and reported a habitual of 7 to 9 hours of sleep per night (mean 7.6; SD .75). In order to avoid confounding influence of circadian rhythm (Lenne et al., 1997) or any diurnal variation (Grace et al., 2010), all experimental sessions were conducted between 9 and 12 in the morning. Participation was compensated either with course credit or €30. The study was conducted in conformity with the declaration of Helsinki (2008).

2.2. STIMULI AND INSTRUMENTS

Eye movements were sampled monocularly at 500 Hz using the Eyelink 1000 remote eye tracking system (SR Research, Ontario, Canada) with a spatial accuracy of <0.5°. Saccades and fixations were measured using the saccade detection algorithm supplied by SR Research. Saccades were identified by deflections in eye position in excess of 0.1º, with a minimum velocity of 30ºs-1 and a minimum acceleration of 8000ºs-2, maintained for at least 4 ms. A 9-point calibration and validation was performed before the start of each session. Saccades around blinks, as well as fixations and saccades with durations less than 100 ms and 10 ms, respectively, were not considered in the analysis.

The fixation task was designed in order to detect changes in saccadic parameters. Therefore, a fixation cross and a visual target were alternately presented. Participants had to continually fixate on the fixation cross and execute a saccade to the visual target as soon as it appeared. The white fixation cross had a size of 0.74 deg and was randomly located on each corner of the screen. The visual target consisted of a red dot (size 0.74 deg) containing a concentric inner black dot with a size of 0.14 deg. Eight different eccentricities between the fixation cross and the visual target were implemented (5, 7.5, 10, 12.5, 15, 17.5 and 20 deg). Saccades had to be made in three different directions (vertical, diagonal and horizontal). Target locations were randomly selected among the eccentricities; the fixation cross always disappeared when the visual target was shown. The background color of the screen remained dark grey during the fixation task. For each eccentricity, the visual target was shown 48 times; the directions were balanced across the eccentricities. One fixation task session consisted of a total of 336 fixation tasks; after every 84 trials, a drift correction was performed. Fig. 1 shows the interface of the task. Completing the fixation task lasted for about eight minutes and it required approximately five minutes changing between fixation and driving task (and vice versa; including the eye tracker calibration).

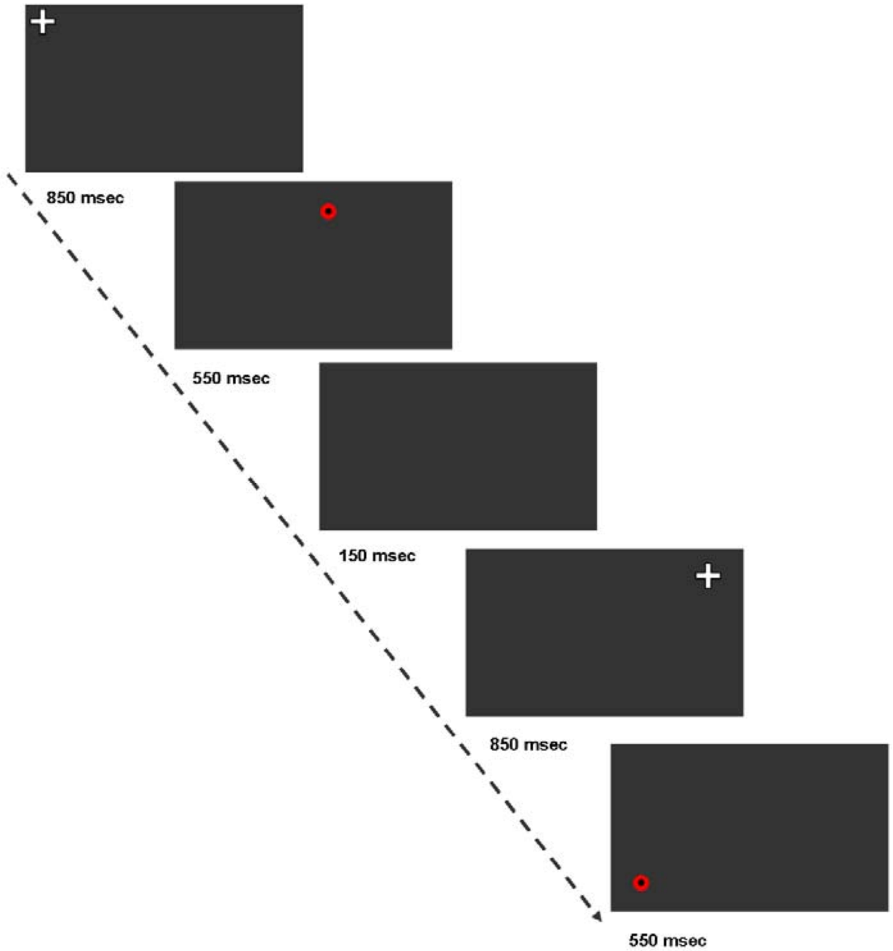

Figure 1. The design and timing of the fixation task.

In order to induce mental fatigue, participants had to complete a two hours driving task using the PC-based SIRCA simulator, developed for eye tracking experiments (for more details, see Velichkovsky et al., 2002 a, b; Di Stasi et al., 2010 a). The road scenario was displayed on a 19 inch screen (1152 x 864 pixels, refresh rate 100 Hz) located in front of the driver, who was seated on a comfortable chair. While driving, the distance to the screen was approximately 80 cm, resulting in a visual angle of approximately 28.5° vertically and 21.4° horizontally. Eye movements were recorded over the whole driving period. Only the frontal view was used. The interaction with the virtual vehicle took place via devices that are typically present in an automatic car; accordingly, the primary controls of the simulator were physical. The steering wheel provided haptic feedback and mechanical response. Speed and central rear mirror were displayed on the monitor. Loudspeakers were located in front of the driver, about 2 meters above the ground, and provided the simulated sound of the engine. Testing took place in an air-conditioned (ca. 22°C), dimly lighted room with minimal background noise. The sample rate of the simulator was about 20 Hz.

The programmed scenarios traversed curved and straight 2- and 4-lane roads, with moderate surrounding traffic. May and Baldwin (2009) suggest that extended driving through monotonous and predictable road conditions could induce task-related passive fatigue. To reach this aim, the task complexity was set to a low level consisting of about 75 cars around the participants' vehicle within a radius of 1.5 km. Participants drove around the same circuit on average 12 times. To complete one entire circuit-loop participants need approximately 10 minutes, depending on their driving speed.

To evaluate the subjective ratings, we made use of four different questionnaires. First, for screening purposes the subjective quality of sleep was measured with the Groningen Sleep Quality Scale (GSQS; Mulder-Hajonides van der Meulen et al., 1980). It consists of 15 true/false statements that are related to the subject's feeling about the difficulty in falling asleep, duration of sleep, sleep fragmentation, and early morning awakening. This questionnaire contained 4 statements with positive scoring, 11 statements with negative scoring; the first statement had no scoring. The maximum score was 14, indicating poor sleep the night before. Subjects who scored higher than 3 at the beginning of the experiment would have been excluded from further testing, which was not the case in our study (Morad et al., 2009). Second, the Stanford Sleepiness Scale was used as a global measure of sleepiness (Hoddes et al., 1973). It contains seven statements describing a gradually increasing feeling of sleepiness ranging from "Feeling active, vital, alert, or wide awake" (score 1) to "No longer fighting sleep, sleep onset soon; having dream-like thoughts" (score 7). Third, the level of fatigue was explored with the German version of the Chalder Fatigue Scale (CFS; Chalder et al., 1993; Bengel et al., 2008); consisting of 14 true/false statements.

According to the literature (e.g. Linden et al., 2006), mental fatigue can also appear as a consequence of continuous mental workload. Thus, we used a German translation of the Mental Workload Test (MWT) for assessing the degree of mental workload experienced by our participants. This questionnaire asked participants to judge 13 bipolar visual scales [low/high at each end]. No numerical values were shown to the participants, but values ranging from 0 to 100 (twenty-one points) were assigned to positions on the scale during data analysis (for more details see Di Stasi et al., 2009).

2.3. PROCEDURE

Subjects' were told that the purpose of the experiment was to evaluate their behaviour in a realistic road environment. The driving task was preceded by a five minutes practice session that allowed the participants to become acquainted with the simulator. The participants were asked to drive the urban environment with a recommended speed of about 50 km/h, to follow the usual traffic rules, not to turn off at intersections and to keep the car mostly in the right lane. Before the start of the experiment, the participants signed a consent form that informed them of the risks of the study and the treatment of personal data.

The experiment started with the set up and calibration of the eye tracking system and the first fixation task session, followed by the two-hour driving task. Afterwards, the second fixation task session was performed. Following the 15 minutes rest break, the third and final fixation task session was performed. During rest break participants went out to the courtyard of the faculty building together with the experimenter. The questionnaires were always completed after each fixation task. In total the experiment lasted for about three hours. Table I summarizes an overview about all recorded indices.

Table I. Summary of the recorded parameters during all experimental sessions

MEASURING TIME / MEASURE	Before driving	During driving	After driving	After the rest break
Subjective rating	GSQS SSS CFS MWT	- - - -	- SSS CFS MWT	- SSS CFS MWT
Eye-movements	Saccadic Dynamic (Fixation task)	Saccadic Dynamic (On-line recording)	Saccadic Dynamic (Fixation task)	Saccadic Dynamic (Fixation task)
Performance	-	Driving Speed	-	-

3. RESULTS

The results section will be organized in the following order: we begin with the analyses and results for the subjective ratings, followed by the outcomes of the fixation task. For the driving task performance data and saccadic behaviour are analyzed. At the end a brief integration of the overall results will be shown.

3.1. SUBJECTIVE RATINGS

First, we analyzed the subjective ratings and the results of the fixation task by conducting single-factor repeated analyses of variance (ANOVA) with three measuring times serving as within-subjects factor: before driving, after driving and after the rest break. The degree of fatigue and mental workload was obtained by the three questionnaires: SSS, CSF and MWT. Mean scores of SSS and CSF as well as averaged MWT scores for each subject and each measuring time were entered into single-factor ANOVAs. Reliable differences were found for SSS scores, $F(2,18) = 9.595$, $p < .005$, $MSE = 0,448$, as well as for CSF, $F(2,18) = 9,9831$, $p < .005$, $MSE = 1,966$ (see Table II). Bonferroni-corrected post-hoc tests showed significant differences for both questionnaires between the first and the second test; for the SSS there was also a difference between the second and third evaluation, all ps $< .05$. A similar tendency was found for the CSF scale (see Table II) but exceeded the significance level, presumably because of insufficient statistical power (sample size = 10). For the MWT, no reliable differences between test times were found, $F(2,18) = 1.021$, $p = .380$, $MSE = 19.56$. Taken together, these results show that the level of fatigue increased over time, while the experienced mental workload remained stable during the whole experiment (see Table II).

3.2. FIXATION TASK

Next, the sensitivity of the saccadic main sequence parameters to the measuring times of the fixation task was analyzed. Amplitudes of the saccades were categorized into 7 bins (henceforth referred to as saccade length). The saccadic-bin analysis (Di Stasi et al., 2010 a, b, c, submitted), i.e. analyzing the PV and saccadic duration as a function of saccade length, represents a valid alternative to the standardization procedure (e.g. Schleicher et al. 2008) and also controls for the influence of saccadic magnitude on PV and saccadic duration. Accordingly, saccade length ranged from 2.5º to 20º (2.5° < Bin 1 < 5º; 5º < Bin 2 < 7.5°; 7.5º < Bin 3 < 10º; 10º < Bin 4 < 12.5º; 12.5º < Bin 5 < 15º;

15º < Bin 6 < 17.5º; 17.5º < Bin 7 < 20º). Obtained medians for saccade duration and PV were submitted to two separate 7 (saccade length) x 3 (measuring time) repeated-measures ANOVAs.

Regarding saccade durations there were main effects of saccade length, $F(6,54) = 432.56$, $p < 0.001$, $MSE = 29.6$, and measuring time, $F(2,18) = 22.376$, $p < 0.001$, $MSE = 9.1$. The interaction of both factors was also reliable, $F(12,108) = 8.245$, $p < 0.001$, $MSE = 1.9$. As expected, longer durations were found for larger saccades. Simple effect analyses of saccade length showed significant differences between test times for saccades larger than 10 deg (bins 4-7), all *p*s < 0.05. Bonferroni-corrected post-hoc tests showed significant differences between the first and second as well as between the first and third measurement, all *p*s < .016. Saccadic duration in the first measurement was longer than the other two conditions (see Table II).

Regarding PV, the ANOVA revealed significant main effects for saccade length, $F(6,54) = 450.54$, $p < 0.001$, $MSE = 523$, and for measuring time, $F(2,18) = 14.586$, $p < 0.001$, $MSE = 1567$. The interaction was also reliable, $F(12,108) = 6.277$, $p < 0.001$, $MSE = 166$, (see Figure 2). Again, simple effects analyses on the different saccade length bins showed significance of measuring time for saccades larger than 7.5 deg (bins 3-7), all *p*s < 0.05 . Again, higher PVs were found for larger saccade lengths. Also, PV Bonferroni-corrected post-hoc tests indicated significant differences between the first and second as well as between the first and third measurement, during the fixation task (*p*s <0.05). PV in the first measurement was higher than in the other two conditions (see Table II). We also considered the individual differences and found that seven out of ten subjects showed the tendency as reported above.

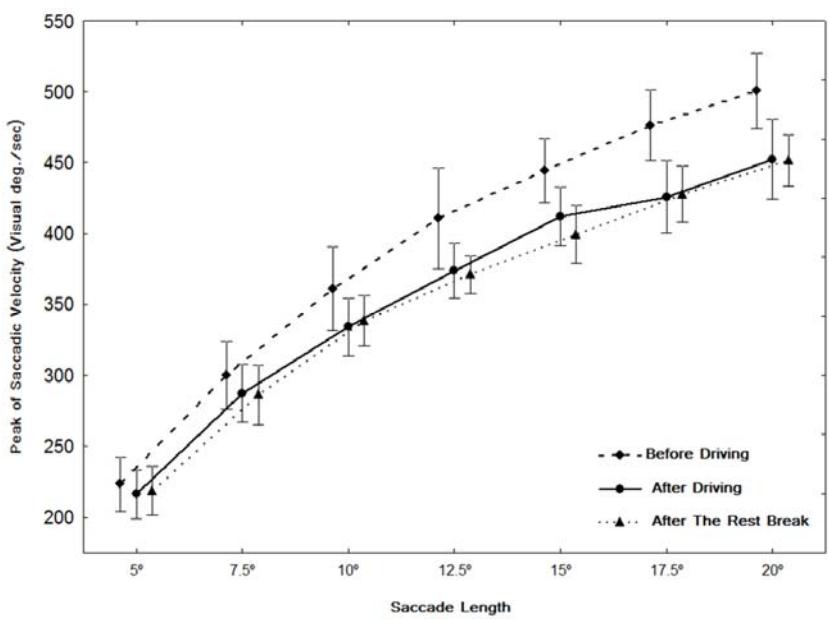

Figure 2. Interaction between measuring time and saccade length for PV. Vertical bars denote 0.95 confidence intervals.

As expected, for all main sequence indices, longer durations and higher PV were found with increasing saccade length (the main sequence rule). More importantly, the interaction effect between saccadic length and test time showed the influence of fatigue on the main sequence parameters, especially in the PV. This effect can be accounted for by considering the nature of these two parameters. When a saccadic movement starts, it has an initial velocity and then accelerates (Becker, 1989). The PV is the point at which acceleration stops. It is independent of saccadic duration and length, whereas the apparent duration of saccades depends on the distance (Becker, 1989). Now, considering that we also analyzed relatively short saccadic lengths (<10º), it is possible that the mathematical relation between these parameters could mask the effect of our main manipulation.

Table II. Subjective and eye motion averages and standard deviations (SD) for each experimental condition. The symbol "*" denotes differences with statistical significance, all *ps*<0.05.

	Before Driving		After Driving		After Rest-break	
	Mean	SD	Mean	SD	Mean	SD
MWT (score)	29.81	11.46	28.11	10.79	27.00	11.43
*SSS (score)	2.20	0.92	3.50	1.35	2.70	1.06
*CSF (score)	0.90	1.10	3.70	2.11	2.20	2.15
*Saccadic Durat. (msec)	42.61	15.84	45.70	18.14	45.40	17.76
*PV (º/s)	388.11	141.66	357.50	122.32	356.18	119.38
*p < 0.05						

Finally, the relationships between scores in the SSS and CSF scales and the PV index were computed separately for the three fixation tasks. No significant linear correlations were observed, all ps > .05 (minimum/maximum absolute value of r = 0/0.63). This result indicates a dissociation between subjective ratings and psychophysiological measures (DeLuca, 2005). This finding is in agreement with earlier reports by Tsang and Velazquez (1996) who demonstrated a relatively low sensitivity of subjective ratings to the state of attention, in contrast with psychophysiological measures and confirmed recent results from our own laboratory (Di Stasi et al., submitted), showing a dissociation between questionnaires and PV.

3.4. DRIVING TASK

The full period of driving (120 minutes) was categorized into six time-on-driving bins (TOD), each consisting of 20 minutes. Each of the six temporal bins included approximately two completions of the simulation circuit. The analysis followed a unifactorial design, with TOD as single factor, manipulated within participants. Mean values of performance of each individual participant (i.e. driving speed) and the sensitivity of saccadic main sequence parameters (i.e. saccadic duration and PV) in relation to changes in TOD were analyzed using a repeated measure ANOVA. The amplitudes of the saccades were categorized in the same way as described for the fixation task. Data of one participant had to be excluded from this analysis because of log-system failures during the recording.

Based on previous results with a similar experimental condition and the same driving simulator (Di Stasi et al. 2010 c), we selected driving speed as the indicator for performance data. This index reflects the driver's continuous effort in terms of forward vision tracking and road hazard monitoring (Wickens at al., 1998). Participants were instructed at the beginning to drive with a nearly constant speed (about 50 km/h). We expected to find a greater deviation from the speed instructions with increasing mental fatigue. Contrary to that, no reliable differences were obtained between the six TOD bins, $F(5,40) = 1.603$, $p > .05$, $MSE = 15,22$ (see Table III). However, speed behaviour is an important factor in road safety (Haglund & Aberg 2002) and it reflects the driver's willingness to expose her/himself to the risk of an accident (Wasielewski, 1984). The present results demonstrate that despite the increased mental fatigue, our participants maintained a constant level of road safety awareness (Wasielewski, 1984),

Analysis of the duration of saccades revealed a significant main effect for saccade length, $F(6,48) = 281.87$, $p < 0.001$, $MSE = 35.61$, and for TOD, $F(5,40) = 3.434$, $p < 0.05$, $MSE = 18.25$, with no interaction, $F < 1$ (see Table III). Bonferroni corrected post-hoc tests did not reveal any significant differences between TOD levels (all ps > .05).

The analysis for PV showed main effects for saccade length, $F(6,48) = 188.10$, $p < 0.001$, $MSE = 2513.66$, and for TOD, $F(5,40) = 4.5793$, $p < 0.005$, $MSE = 839.04$, and a significant interaction, $F(30,240) = 1.815$, $p < 0.01$, $MSE = 383.108$ (see Table III). Simple effects on each single TOD bin demonstrated significant effects for bins 1, 2 and 5, all ps < .001. Moreover, simple effect analyses on each single level of TOD factor showed that the PV started to decrease after one hour of driving ($p < 0.01$).

A possible explanation for these findings could be the gradual deactivation of driver (see Galley, 1989). We assume that the driver activation state started to decrease already after one hour of driving, reaching the minimum level (i.e. maximum level of fatigue) at the end of the driving session (as also manifested in results of the fixation task). This interpretation is in line with earlier findings by Schleicher et al. (2008) who found in a similar driving task an insurmountable level of sleepiness (which even led to the termination of the experiment) was reached after approximately 130 minutes.

However, drowsiness already reached saturation after about 90 minutes. Following these findings, it might be plausible that also our participants were exhausted already after 80 minutes of driving. The implication then would be that the PV is not sensitive to further decreases in activation within the remaining 40 min of driving.

Table III. Averages and standard deviations for speed, saccadic duration and PV according to time-on-driving. The symbol "*" denotes differences with statistical significance, all ps<0.05.

	20′		40′		60′		80′		100′		120′	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Driving Speed (Km/h)	44.22	5.99	48.15	6.82	46.90	7.94	47.40	9.34	48.48	9.38	48.64	8.36
*Saccadic duration (msec)	44.03	12.86	44.85	13.18	45.64	13.42	46.73	13.41	46.31	13.27	46.00	12.89
*PV (º/s)	363.46	100.64	263.78	99.53	352.05	91.12	347.50	88.62	248.65	92.31	347.25	91.62
*p < 0.05												

4. DISCUSSION

To recapitulate, according to DeLuca (2005), fatigue depends on time on task and task complexity. In general, fatigue is reflected by an increase in the subjective evaluation of tiredness together with a decrement at the execution level. In this case—to explain for stable performance index—there might have been increased effort by the participants to maintain an acceptable level of performance and to compensate for the increasing fatigue. This mechanism has already been suggested by DeLuca (2005). For this reason we think that mental fatigue effects can be addressed in the disruption of main sequence rules (i.e. for a giving amplitude a decrease of PV and saccadic duration), in line with the original work of Schmidt et al. (1979) or some recent results (e.g. Hirvonen et al., 2010; Di Stasi et al., submitted). In conclusion, we argue that the results of both tasks (driving and fixation task) support the idea that the PV is an appropriate candidate to detect changes in activational driver state.

To be fatigued while driving is considered one of the most important safety issues in transportation. Here we report a new sensitive measure of mental fatigue investigated in relation to continuous driving. Our measure is based on the behaviour of the PV by measuring eye movements in a simple fixation task before and after two hours of driving as well as subsequent to a short rest break.

There are three main findings. First, driver fatigue increased with longer driving in the simulator as indicated by the subjective ratings of mental fatigue. The main sequence rules seemed to be affected by this variation in mental state: PV became smaller with increasing fatigue. Moreover, we found that after a rest break of 15 minutes, the main sequence did not reach the level at the beginning of the experiment. Accordingly, our study contributes to the investigation of saccadic velocity characteristics, hereby supporting earlier reports by Schmidt et al. (1979) and previous research from our laboratories (Di Stasi et al., 2009; Di Stasi et al., 2010 a, b, c, submitted).

Second, a rest break of 15 minutes was not enough to increase the driver's physiological arousal, as indicated by the values of the PV. Our results are in line with earlier observations by Nilsson, Nelson and Carlson (1997) and Smiley (2007) who found that subjects were not able to appropriately quantify their level of fatigue. According to the subjective evaluation (results of the SSS and CSF), participants reported less fatigue after the break; in contrast, main sequence results show only little impact of the rest break.

Of particular interest from the perspective of theoretical implications and for the objective analysis of human functional state is the dissociation between eye movement data and subjective reports concerning the recovery after the break. Similar effects have already been described in the literature as a dissociation of psychophysiological indices of stress, fatigue and questionnaire data (Leonova, 1997). While these earlier reports were rather concerned with long-term (chronic) effects of occupational stress, here we address instantaneous changes in the human functional state. The current findings provide promising evidences but further work is required to validate this short-term dissociation of PV from subjective reports as a real index of fatigue. Future research should involve various independent psychophysiological measures of the human functional state.

Finally, according to the subjective ratings, the differences between measuring times (e.g. the time-on-task) are not related to various levels of mental workload experienced by the driver. This point is important for disentangling effects of mental workload and fatigue on the main sequence (Di Stasi et al., 2010 c, submitted). No relationship was observed between the measuring times and the amount of experienced mental workload. Thus, the modulation of the main sequence cannot be related to variations of the mental workload as measured in this study. It might be possible to observe this modulation using more highly sensitive measures of mental workload. A detailed discussion of the relationship between fatigue and mental workload is beyond the scope of this work; however, further investigations are required, particularly with the use of complex and dynamic scenarios.

Further work is also needed in order to generalize our observations: First, the lack of a control condition/group might weaken our results. However, the driving task results, together with previous observations (Hirvonen et al., 2010, Di Stasi et al., 2010 b, submitted), led us to assume that the increase in mental fatigue was related to the driving task (relatively monotonous road environment), which is also in line with earlier findings (Schleicher et al. 2008). Furthermore, a recent investigation by Grace et al. (2010) partly confirmed our hypothesis: the change in PV was related to the driving task than to the general organism's diurnal variation. Grace and colleagues demonstrated that the PV of healthy people—completing a control task between 9 am and 1 pm—started to decrease after 11 am. Since the driving task in our study was terminated around 11 am, diurnal variation cannot explain our findings. Second, the effect of the rest was evaluated only for a break of 15 minutes; longer resting periods are expected to more strongly decrease the fatigue level. In this case, with regard to the abovementioned research, we cannot rule out that some marginal diurnal variation effects influenced the results on the final fixation task (after the rest break). Third, the effects of fatigue were only investigated in virtual environments, not in real life. In relation to this, it is required to develop an on-line measurement; here we used the fixation task while driving was interrupted. This approach was chosen to examine the general idea first, in a well-defined and controlled setting.

5. CONCLUSIONS

Detecting when daily tasks become mentally fatiguing is a first step towards effective management. Most jurisdictions limit the maximum number of hours that can be driven per day (or per week). Moreover, there are definite specifications regarding the timing and duration of rest periods. However, the effectiveness of these regulations can be questioned on several reasons. One reason is that the legislative approach omits important factors that affect alertness levels, such as time of day, prior activity, etc. (Haworth, 1995). Instead of these inflexible regulations, systems for the detection of driver fatigue could be a good alternative for improving safety issues in transportation. During the last ten years, fatigue measurement instruments have been developed that can be characterized as "fatigue warning systems" (e.g. Onken et al, 1997). Most of these systems use indices computed upon the duration and frequency of eye blinks, for example PERCLOS (Wierwille et al., 1994; Dinges & Grace, 1998). As explained in the introduction, the use of blink- or pupil- related fatigue measures has intrinsic problems when applied to ecological and less artificial conditions. For this reason, we looked for an alternative index that can be applied to ordinary vehicles (from trucks to aircrafts).

Several studies have shown the sensitivity of the main sequence parameters to variations in mental state in controlled laboratory situations (for example: Schmidt et al, 1979; Di Stasi et al., 2010 a, b, Hirvonen et al. 2010). Our results demonstrate that PV discriminates between various levels of mental fatigue produced by the continuous performance of complex dynamic tasks. In other words, PV can be used as a valid predictor of the variations in mental fatigue that emerges when people are engaged in long-lasting and repetitive dynamic tasks.

Our results are especially important for the study of fast parameters of saccadic movements as indices of the second-by-second (indeed sub-second) variability in mental fatigue. In the framework of this experiment, we proposed video-oculography as a reliable measurement solution that can monitor unexpected and continuing changes in driver mental state (Farmer & Brownson, 2003). As discussed by Lal and Craig (2001), these technological solutions have several disadvantages including high costs and the need for calibration; in addition, the system might not work when sunglasses are worn. However, since the investigated parameter is based on the relation between amplitude and velocity of saccades, the development of a device in accordance to the technology of EEG/EOG might be possible. If applicable, the electrodes should be chosen in order to cover just the eye region using the 3/4-channel EEG. Such a solution could detect these changes, with only three electrodes positioned on the face of the driver. Nowadays, with the use of active electrodes, including integrated noise subtraction circuits and Wi-Fi solutions, there are optimal premises for the implementation of a reliable "tool" for measuring the attentional state (Tsang & Wilson, 1997). For such a solution, a compromise has to be made between sensitivity, intrusiveness and, most of all, the operator's acceptance.

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CHAPTER VI

Saccadic peak velocity as a driver attentional index

Saccadic peak velocity sensitivity to variations in mental workload

CHAPTER VI

Saccadic peak velocity as a driver attentional index

Saccadic peak velocity sensitivity to variations in mental workload

ABSTRACT

For research and applications in the field of (neuro)ergonomics it is of increasing importance to have reliable methods for measuring mental workload. In the present study we examined the hypothesis that saccadic eye movements can be used for an on-line assessment of mental workload. Saccadic main sequence (amplitude, duration and peak velocity) was used as a diagnostic measure of mental workload in a virtual driving task with three complexity levels. Eighteen drivers were tested in the SIRCA driving simulator while their eye movements were recorded. The Wickens' multiple resources model was used as theoretical framework. Changes in mental workload between the complexity levels were evaluated multidimensionally, using subjective rating, performance in a secondary task, and other behavioural indices. Saccadic peak velocity decreased (7.2 visual °/s) as the mental workload increased as measured by scores of mental workload test (15.2 scores) and the increase of the reaction time on the secondary task (46 ms). Discussion: Saccadic peak velocity is affected by variations in mental workload during ecologically valid tasks. We conclude that saccadic peak velocity could be a useful diagnostic index for the assessment of operators' mental workload and attentional state in hazardous environments.

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1. NTRODUCTION

Due to the limitation of high visual acuity to the small foveal area (about 2 degrees of arc) eye movements are essential for our visual perception. Therefore, saccades—fast ballistic movements—are performed that bring the eyes' foveal area from one point of interest to another. These saccadic eye movements vary in amplitude, duration, and peak velocity (PV). The relationship between these three parameters has been called the "main sequence," to indicate that PV and saccadic duration increase systematically with the amplitude (Becker, 1989). It is of importance for the purpose of the current study that the PV is independent of the saccadic duration since it is not linked to it, a priori, by a mathematical definition, like saccadic velocity (Becker, 1989). However, the relationship between PV and amplitude seems to be more complex than has previously been assumed (Schmidt et al., 1979). There is evidence of variations in PV depending on the mental resources required to perform different tasks (App & Debus, 1998). These variations could be independent of the saccadic amplitude. Recent research (e.g., Di Stasi et al. 2009) has demonstrated that mental workload and/or fatigue affects the dynamics of saccades and that PV could be an appropriate measure of this relationship. In the present work, we report further results supporting the idea that PV is a measure of mental workload in complex environments.

Mental workload is an important factor in human performance in complex interactive systems. It is defined as the amount of cognitive capacity required to perform a given task (O'Donnell & Eggemeier, 1986). It therefore refers to "a composite brain state or set of states that mediates human performance of perceptual, cognitive and motor tasks" (Parasuraman & Caggiano, 2002). The multiple resources model developed by Wickens (Wickens & Hollands, 2000) is a theoretical framework for workload assessment related to human information processing. The model provides an explanation for mental activity changes that follows after changes of the operational conditions (e.g., task difficulty, time pressure). According to the Wickens' model, attentional resources can be categorized along three dimensions: a) input/output modalities; b) processing codes; and c) response execution. Accordingly, high similarity in the resource demands imposed by the task components leads to a severe competition for similar resources which will result in a high level of workload. This could be the case, for example, due to high demands of perceptual or working memory processing.

Although research on eye movements has focused on the relation between saccadic amplitude and fixation duration, the velocity of saccades is commonly considered to be a simple correlate of the amplitude, and PV to be a nonlinear transformation of saccadic amplitude (e.g., Pannasch et al., 2008). Furthermore, App and Debus (1998) have suggested that saccadic velocity has not been considered as an index of mental state because it is strongly dependent on saccadic amplitude and orbitary direction and is frequently uncontrolled in real-life contexts. In fact, very few studies have explored the dynamics of saccades in dynamic complex tasks, especially those related to ergonomics and real-life applications.

In the literature, eye movement parameters (e.g., Schleicher et al., 2008) and performance data (Stone et al. 2003) are used as indicators of fatigue. In the present study, we aim at extending previous research by using a more complex setting in which subjects completed a virtual driving task with different complexity levels. The purpose was to explore the sensitivity of the saccadic main sequence, particularly PV, to changes in the operator's mental state.

2. METHODS

2.1. PARTICIPANTS

Eighteen healthy students of the Technische Universität Dresden, took part in this experiment; 9 females and 9 males ranging in age from 19 to 33 yr (mean age 24). All subjects had normal or corrected-to-normal vision, were holders of a driving license (from 0.5 to 15 yr) and signed a consent form that informed them of the risks of the study and the treatment of personal data. They received either course credit or € 7 for participating in the study. The study was conducted in conformity with the declaration of Helsinki.

2.2. STIMULI AND INSTRUMENTS

Eye movements were sampled monoculary at 500 Hz using the Eyelink II head-mounted eye tracking system (SR Research, Ontario, Canada). Spatial accuracy was always better than 0.5°. Saccades and fixations were measured using the saccade detection algorithm supplied by SR Research. Saccades were identified by deflections in eye position in excess of 0.1°, with a minimum velocity of $30°s^{-1}$ and a minimum acceleration of $8000°s^{-2}$, maintained for at least 4 ms. A 9-point calibration and validation was performed before the start of each session. Fixations around blinks, as well as fixations and saccades with durations less than 100 ms or 10 ms, respectively, were not considered in the analysis.

Subjects were tested on the PC-based SIRCA driving simulator, developed and adapted for eye tracking experiments. The driving scenarios consisted of an urban environment and were designed for the training of dynamic and complex time-critical driving skills, including situational awareness, hazard perception and risk assessment. A hazard is any object, condition or situation that tends to produce an accident when drivers fail to respond correctly. The driving environment was projected onto a 1.5 × 2 meter screen; with a distance of 3.5 meters the resulting view angle was about 24° vertically and 32° horizontally. Only the frontal view was used. Speed and central rear mirror view were displayed on the monitor. Loudspeakers located in front of the subject at about 2 meters from the ground provided engine and other acoustical feedback. The sample rate of the simulator was about 20 Hz.

As a secondary task, potentially hazardous situations were produced by pop-up events. They appeared in the central field of view in a perceived distance of 20 meters in front of the participant’s car. The events were red squares and rectangles. Each type of event was associated with a specific reaction. Subjects were asked to press the left or the right button of the steering wheel in response to the squares and rectangles, respectively. The hazard remained present until subjects responded correctly; in the case of no response or an incorrect response, the events disappeared about 12 meters in front of the car. Accordingly, the events varied in size from 2.4° to 3.9°. Sixty events in each simulation block were displayed (depending on the speed) on a projection screen at random time intervals. In half of the cases an auditory warning signal was given 500 ms before the event appeared. It was presented with a noise level of 75 dB and a duration of 370 ms. The sounds were a 740 Hz double-beep tone or one of two affectively charged voices: a woman’s scream (negative valence) and a baby’s laugh (positive valence), selected from the IADS (Bradley & Lang, 1999); numbers 277 and 110, respectively). [Note: Fundamental feature of the abstract neutral sound: Fundamental frequency (Hz) = 740; Harmonics = 4; Signal type = Sine; Amplitude (dB) = 0; Pulse rate (Hz) = 6.3; Pulse length = 0.079; Silence length = 0.079; Envelope = T1.]

2.3. DESIGN

In this experiment three different levels of task complexity (low, medium and high) were created by manipulating traffic density and giving a secondary task. Traffic density could either be low (no other cars) or high (comparable to a rush hour in a European city; about 500 simulated cars around the subjects’ vehicle within a radius of 1.5 Km) and was assumed to affect the load of information processing (Wickens & Hollands, 2000). Low task complexity was defined as driving with low traffic density and no secondary task. Medium task complexity involved low traffic density and a secondary task. In the high complexity task condition, high traffic density was combined with the secondary task. To disentangle mental workload and fatigue the order of tasks was varied in the following way: all subjects started with the low task complexity, while the order of medium and high complexity tasks was balanced across the subjects.

We used a multiple measures approach to evaluate the effectiveness of the task complexity manipulation. First, the Mental Workload Test (MWT), developed by the Cognitive Ergonomics Group, was used to estimate subjective mental workload. The instrument consists of 13 scales [for more details, see di Stasi et al. (2009)]. Second, driving speed for each complexity level was analyzed. Third, mental workload was estimated from the reaction times to the secondary task (only in medium and high complexity tasks). To estimate possible effects of changes in the mental workload on indices of eye movements we analyzed saccadic amplitude (degrees of visual angle), saccadic duration (milliseconds), saccadic velocity (degrees of visual angle/millisecond) and PV (degree of visual angle/second).

2.4. PROCEDURE

At the beginning of the experimental session, subjects received a general description of the structure of the experiment together with detailed instructions for their tasks. During a short briefing, participants were informed that their ocular movements will be recorded. Before the start of the experiment they were invited to read and sign the informed consent form. The study consisted of two practice sessions and three experimental blocks. During the first practice session, subjects learnt the association between the events (32 trials, square or rectangle) and the correct response (left or right button press, respectively). Within each trial an event was displayed on a static screenshot of the driving simulator. After each response a visual feedback (wrong or correct) was shown. The subjects had to repeat the practice session if the error rate was at 25% or above. In the second practice session, the subjects had to drive for 5 min without any other traffic and to respond as fast as possible whenever a hazard event appeared. The subjects were instructed to drive through the urban environment at the recommended speed of between 40 and 60 km/h, to follow traffic rules, not to turn off at intersections, and normally to keep the car in the right lane. The experimenter supported the subjects by describing the correct procedure in the case of accidents and answering any questions related to the tasks.

After the practice sessions were completed, the eye tracking system was set up and calibrated. Next, the subjects drove for three experimental blocks. The first block lasted for 10 min and was always of low task complexity. Afterwards, the medium and high complexity tasks (10 min each) had to be completed. All subjects had to fill in the MWT after each experimental block.

3. RESULTS

We first examined the effectiveness of the task complexity manipulation by analyzing the MWT, driving speed, and reaction times in the secondary task.

The mean scores of the MWT scales were submitted to a 3 (task complexity: low, medium and high) repeated measures analysis of variance (ANOVA). Significant effects were observed for task complexity [$F(2,34) = 37.55$, $P < 0.001$, $MSE = 333.8$], confirming that the experienced mental workload changed in concordance with the experimental manipulation (see Table I).

The averages of driving speed for each subject and each task complexity were analyzed using a repeated measures ANOVA, with task complexity as the repeated factor. As expected, we obtained reliable differences between the three complexity levels [$F(2,36) = 32.98$, $P < 0.01$, $MSE = 29.5$]. Bonferroni corrected post-hoc comparisons revealed reliable differences in driving speed between all pairs of task complexity (all *ps* < 0.004; Table I).

For the analysis of the reaction times, only the correct responses (93.2%) were selected. Three subjects were excluded from this analysis because of log-system failures during the experimental recording. Geometric means of reaction times were submitted to a 2 (task complexity, medium vs. high) × 4 (warning signal type) repeated measures ANOVA. We found significant main effects for task complexity [$F(1,14) = 5.46$, $P < 0.05$, $MSE = 11{,}535.4$; (Table I) and warning signal type [$F(3,42) = 3.313$, $P < 0.05$, $MSE = 17{,}342.3$], but the interaction between the two factors was nonsignificant [$F(3, 42)=1.28$, $P > 0.05$]. Bonferroni corrected comparisons of least square means indicated reaction time differences only for neutral and negative warnings with respect to the no warning condition [$t(14) = 4.00$, $P < 0.002$, and $t(14) = 4.65$, $P < 0.001$] (Table II). It is possible, that the negative as well as the neutral warning signal primed the participant's attention (Lee et al., 2002) triggering mental processes that may contribute to the response of the secondary task. The nonsignificant interaction between task complexity and warning signal type indicates that for both mental workload conditions, all warning signals appear to have the same effects.

Table I. Overview of the experimental results

	Low Complexity		Medium Complexity		High Complexity	
	Mean	SD	Mean	SD	Mean	SD
MWT (score)*	29.33	9.81	36.50	12.67	44.54	11.44
Speed (KPH)*	48.22	1.11	45.26	1.30	34.60	1.83
React. Time (ms)*	-	-	676.43	39,85	722.02	34,25
Saccadic duration (ms)	48.37	2,68	50.26	3.00	48.32	2.45
Sac.velocity (visual deg/ms)	0.12	0.007	0.12	0.006	0.12	0.007
PV (visual deg/s)*	265.46	16.09	252.40	19.90	258.27	17.22
* $P < 0.05$						

In the next step we analyzed the sensitivity of saccadic main sequence parameters to changes in mental workload. The amplitudes of the saccades were categorized into 9 bins (henceforth saccade length), ranging from 0.01° to 15.9° (0.01° < Bin 1 < 0.9°, 0.9° < Bin 2 < 1.9°, 1.9° < Bin 3 < 3.9°, 3.9° < Bin 4 < 5.9°, 5.9° < Bin 5 < 7.9°, 7.9° < Bin 6 < 9.9°, 9.9° < Bin 7 < 11.9°, 11.9° < Bin 8 < 13.9°, 13.9° < Bin 9 < 15.9°). Three repeated measures 3 (task complexity) × 9 (saccade length) ANOVAs were calculated on the medians of saccadic duration, velocities and PV, respectively.

Analysis of the duration of saccades revealed a significant main effect for saccade length [$F(8136) = 635.87$, $P < 0.001$, $MSE = 29.6$] but not for task complexity. The interaction was found nonsignificant. As expected, longer durations were obtained with increasing saccade lengths(Table I).

Similar results were observed for the velocity of saccades. The analysis showed only significant main effects for the saccade length [$F(8, 136)=1397.5$, $P < 0.001$, $MSE= 0.000615$], but not for task complexity (Table II)

The analysis for the PV showed main effects for saccade length [$F(8136)= 590.07$, $P < 0.001$, $MSE = 1530.4$] and for task complexity [$F(2,34) = 3.869$, $P < 0.05$, $MSE= 1793.6$] but not for the interaction (Figure 1). Bonferroni corrected posthoc tests revealed significant differences between low and high level of task complexity, $P < 0.05$. As the result of this reliable influence of task complexity on PV, this parameter appears to be a promising indicator for the differentiation of mental workload (Table I)

Table II. Effect of the warning signals on the secondary task

	Abstract Sound React. Time (ms)		Negative React. Time (ms)		Positive React. Time (ms)		No Sound React. Time (ms)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Low Complexity	-	-	-	-	-	-	-	-
Medium Complexity	691.58	31.987	616.07	26.376	657.61	27.895	740.48	24.539
High Complexity	697.53	26.859	708.00	20.789	699.50	45.62	783.07	36.77
* $P < 0.05$								

Due to the fact, that mental fatigue might impair performance after longer periods of demanding cognitive activity (Lorist et al., 2005), we also analyzed possible influences of the time on task on the PV. The design of this experimental investigation allows differentiation between the effects of fatigue and changes in mental workload from the same data set. We therefore rearranged the PV data according to the order of task completion (i.e., collapsing over different task complexities) obtaining the new variable time-on-task (TOT) consisting of two levels: intermediate vs. last experimental block. Data were submitted to a 2 (TOT) × 9 (saccade length) repeated measures ANOVA. A main effect was found for saccade length [$F(8136) = 630.72$, $P < 0.001$ $MSE = 957$], but neither for TOT nor for the interaction.

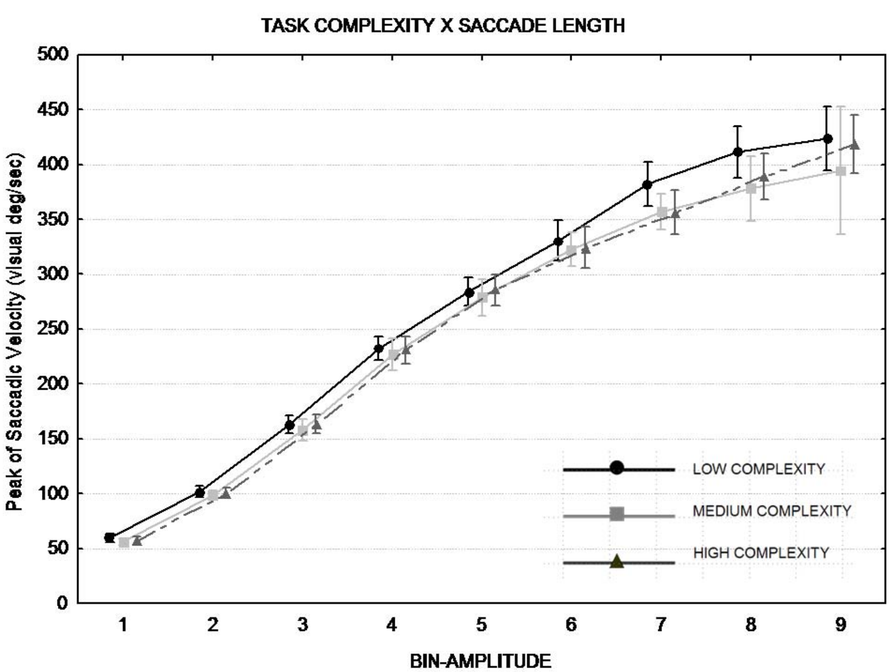

Figure. 1. Illustration of the interaction between Task Complexity and Saccade length factors. Vertical bars denote 0.95 confidence intervals

4. DISCUSSION

In the current research we manipulated the level of task complexity in a virtual driving environment. The results obtained from the subjective ratings (MWT) and behavioural measures (driving speed and secondary task performance) indicate that the blending of different traffic densities and a secondary task can be used to induce different mental workload levels. Driving in a natural environment could similarly be differentiated as low vs. high mental workload conditions by comparing an empty street vs. finding the way during the rush hour in a European city. We next investigated all parameters of the saccadic main sequence (duration, velocity and PV) with respect to the mental workload levels. We found a clear relationship with task complexity only for PV.

Though clear differences in PV were obtained between conditions of low vs. medium/high task complexity, no further differentiation could be made between medium and high task complexity. A promising explanation for this finding can be found in Wickens' model (Wickens & Hollands, 2000). The secondary task that differentiates medium and high complexity tasks from the low complexity condition saturates the visual resource channel. Consequently, adding traffic density to produce a further increase in task complexity is not reflected in the visual channel (i.e., no difference in PV). However, for the resources of other channels (e.g., the answer channel), measurable increases in reaction time (and, more generally, in subjective ratings of mental workload) differentiate between medium and high complexity tasks. This clearly shows the dichotomy between perceptual/cognitive versus response resources, as suggested by Wickens (Wickens & Hollands, 2000).

There are some limits in our study, however. For the tasks and environment used in our study, the analyses for influences of TOT on PV revealed no effects, therefore demonstrating that the modulation of PV cannot have been caused be fatigue. It is possible, however, that fatigue effects can be observed with longer sessions. We think that the relationship of fatigue and mental workload needs further investigations using complex and dynamic scenarios.

The general results reported here support our claim that PV is a promising measure of mental workload in human factors and applied ergonomics without the typical problems of the classical eye movement measures, such as blinking rate and pupil diameter (Wickens & Hollands, 2000). The present study confirms previous findings with simulated motorcycling behaviour (Di Stasi et al., 2009).

To summarize, we demonstrated the saccadic peak velocity to be sensitive to variations in mental workload during ecologically valid driving tasks. We suggest that saccadic peak velocity could be a useful general indicator for the assessment of operators' mental workload and attentional state in hazardous environments. The current work could be a starting point for further research on understanding how variations of cognitive processing and mental workload are reflected in the dynamics of eye movements during ecologically valid tasks. This approach can be useful also for developing operator support systems that will be able to reduce the risk of accidents due to mental overload and distraction.

5. ACKNOWLEDGEMENTS

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CHAPTER VII.

General conclusion: from a mini-review to some personal “speculations”

Saccadic peak velocity as an attentional state index: A short overview

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ABSTRACT

Experimental and theoretical evidence indicates that saccade dynamics contains information about the subject’s performance in naturalistic tasks and applied research approaches. Here we propose to use the saccadic peak velocity [PV] as a measure or index of mental state. We present the historical developments on PV from psychological and clinical research, and their most recent applications to clinical, military, and everyday life situations. We moreover discuss the sensitivity and validity of PV in the identification of mental state variations and its potential diagnostic value in the field of applied ergonomics.

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1. INTRODUCTION

Eye movements are essential for visual perception. Saccades -fast ballistic eye movements- bring successive regions of interest onto the fovea, and so they are crucial to task performance, both in everyday life and in visual monitoring situations such as air traffic or nuclear platform control (Wang, 1998). Since the seminal investigations on eye movements (Volkmann, 1846; Lamansky, 1869), great interest has been shown in studying saccadic velocity (for a detailed revision about the history on eye movements research see Wade and Tatler, 2005). Later Dodge and Cline (1901) and others (see below) established that saccadic eye movements vary in amplitude, duration, and velocity. Saccadic Mean Velocity (MV), Peak Velocity (PV), and duration increase systematically with saccadic amplitude (see Figure 1), a relationship known as the 'main sequence' (Bahill et al., 1975). (The term 'main sequence' was borrowed from the field of astronomy, where it conveys the relationship between the brightness of a star and its temperature). Despite some initial interest in the potential use of the main sequence as an index of mental state, saccadic dynamics have received little attention in applied research. Here we discuss how the field of vision research attempted -and failed- to develop an eye-related index of mental state. We identify the obstacles that remain in the way of a successful index, and the gaps in knowledge that future studies should fill.

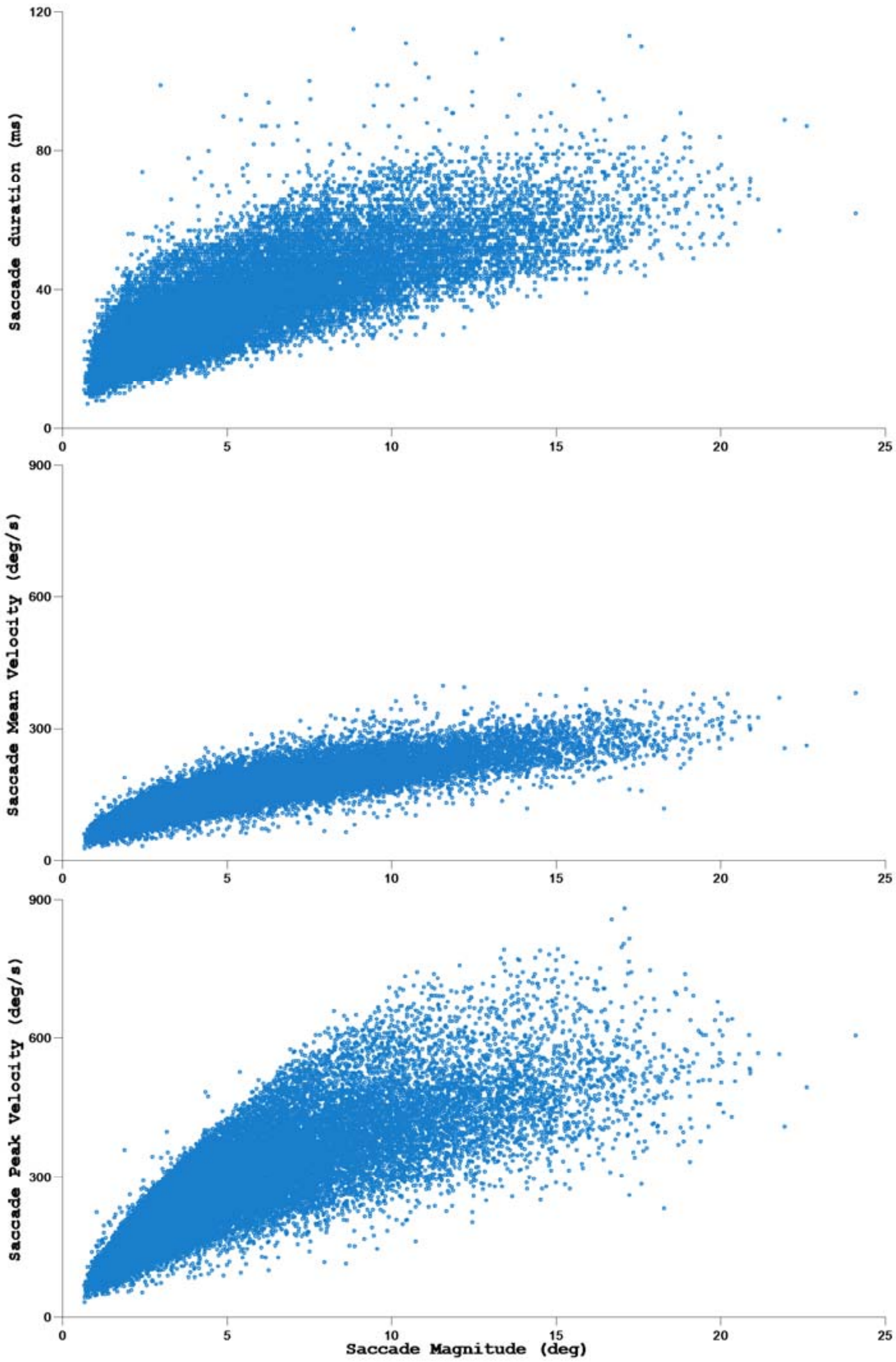

Figure 1. The saccadic main sequence.

Top: Relation between saccade duration and magnitude. Middle: Relation between saccade mean velocity and magnitude. Bottom: Relation between saccade peak velocity and magnitude. N=33,275 saccades [average amplitude (X = 4.94 deg; SD = +/- 3.55); average PV (X = 262.85 deg/s; SD = +/- 128.68); average MV (X = 140.54 deg/s; SD = +/- 58.37); average duration (X = 33.50 s; SD = +/- 13.95). Eye movements from human observers were sampled binocularly at 500 Hz using the Eyelink 1000 remote eye tracking system (SR Research, Ontario, Canada) with a spatial accuracy of <0.5°. Saccades were identified with a modified version of the algorithm developed by Engbert and Kliegl (6 standard deviation parameter, 3 ms duration parameter (Engbert & Kliegl, 2003). To reduce the amount of potential noise (Engbert, 2006), only binocular saccades were & Mergenthaler 2006; Laubrock, et al., 2005).

2. PARAMETERS OF SACCADIC DYNAMICS

Research in saccade dynamics has focused on four main parameters: latency, duration, acceleration, and velocity (Figure 2).

Latency is the simple reaction time from target presentation to saccadic onset. It is affected by a variety of factors (Carpenter, 2004) such as stimulus amplitude and intensity (Bartz, 1962) and it is modulated by practice (Zeevi & Peli, 1979; Di Russo et al., 2003).

Saccadic duration is defined as the time taken to complete the saccade from the eye's initial position to the target's location. It is composed of two phases: the acceleration duration [Da] and the deceleration duration [Dd]. Da is the time required to reach the maximum velocity during the saccade, Dd is the time from the PV to the end of saccade.

The saccadic velocity waveform is symmetric for small saccades (<10º), that is, the acceleration/deceleration phases are equal in length and the PV is reached at approximately half of the saccadic duration (Leigh & Zee, 1999). (This feature may reflect the duration of the activity of burst neurons in the pontine reticular formation. Bahill and Stark (1975 b) found that the pulse portion of the motoneuronal saccadic controller signal is shorter than the duration of saccade, approaching one-half its amplitude. Therefore the PV should be reached around the end of the controller signal pulse being intimately associated with the maximum firing rates of burst neurons (Galley, 1989)).

For saccades bigger than 10º the velocity profile becomes skewed: the acceleration phase is shorter than the deceleration phase, so the PV is reached earlier, at about 1/3 of the total duration of the saccade (Lin et al., 2004).

The saccadic amplitude or magnitude is defined as the total distance covered by the eyes to reach the target, thus the saccadic mean velocity [MV] can be expressed as the ratio between saccade amplitude and duration.

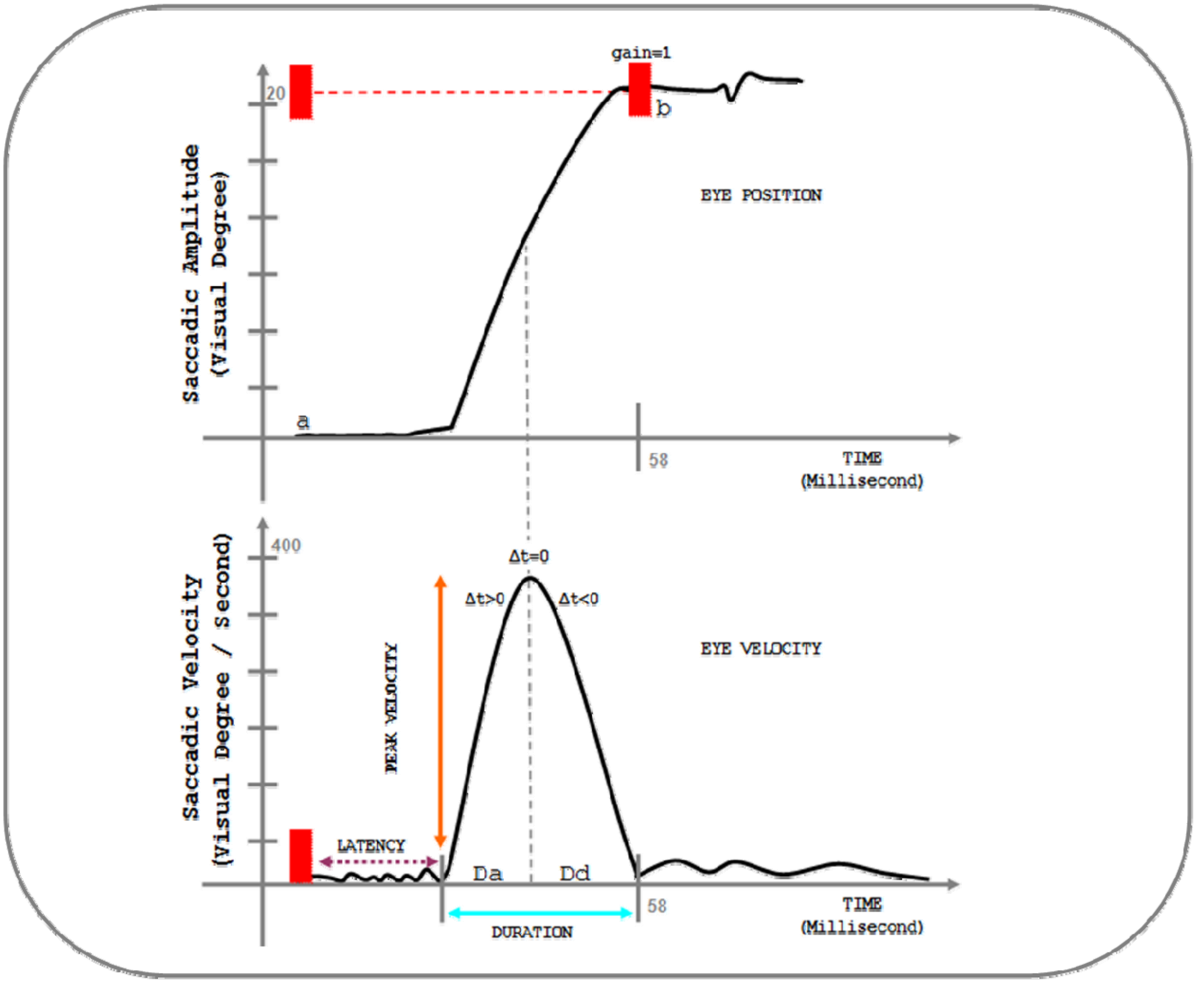

Figure 2. Parameters of saccadic movement

Top: The red dotted line represents the trajectory of a visual target (red rectangle) in space. The black line shows a saccade made in response to a 20º target movement. The y-axis indicates the Euclidean distance between the points [a, b] for each instant over time (x-axis) until the eye reaches the target. The ratio of saccade amplitude to target amplitude (i.e. gain) indicates the saccade's accuracy or precision. A gain of 1 indicates a completely accurate saccade.
Bottom: Velocity profile of the saccade. The eyes start off at rest (left), accelerate to reach the PV early in the course of the movement, and then slowly decelerate as they approach the target. The saccadic latency is the time from the target's appearance to the start of the saccade. The saccadic PV is the highest velocity reached during the saccade. The acceleration time (Δt>0) indicates the time from the start of the saccade to the PV. The deceleration time (Δt<0) indicates the time from the PV to the end of the saccade. The acceleration is null (Δt=0) at the PV. The saccadic duration is the overall time taken to complete the saccade.

Galley (1989) observed that MV and PV have an approximate ratio of 1 to 2 in their absolute values and pointed out that, although MV and PV correlate highly. Di Stasi and colleagues (Di Stasi et al., 2010 d; Di Stasi et al., submitted a) later found that increased task complexity* led to decreased PV and unchanged MV in simulated driving

*Before reading the next sections, there are three terms that have to be defined to better understand the contents of this work: task complexity, mental workload, and mental fatigue. ***Task complexity*** is defined as a tasks and complex visual task, suggesting that PV is a more sensitive index of attentional state variations than MV or saccadic duration (see section 3.6. Everyday life domains, for further details).

Despite these distinctions, several authors refer to “saccadic velocity” (e.g. Russo et al., 2002; Thomas & Russo, 2007; Morad et al., 2009) without specifying if the value corresponds to MV or PV, and sometimes PV and MV are used interchangeably (e.g. De Gennaro et al., 2000).

3. PV AS AN ATTENTIONAL INDEX IN APPLIED DOMAINS

Human eyes are outgrowths of the brain and thus part of the central nervous system (Hoar, 1982; Wilson & O’Donnell, 1988); therefore gaze parameters may be used as reliable indicators of attentional or mental state (see for example: Ahlstrom & Friedman-Berg, 2006; Schleicher et al., 2008; Dey & Mann; 2010). Studies have generally focused on the relationship between saccadic amplitude and fixation duration (for example: Unema et al., 2005; Graupner et al., 2007; Pannasch et al., 2008), rather than on specific saccadic dynamics such as velocity. Unlike saccadic amplitude or fixation duration, however, saccadic velocity is not subject to voluntary control (Leigh & Zee, 1999); thus an attentional index based on saccadic velocity may provide an accurate representation of the subject’s involuntary variations in mental state (Rowland et al., 2005).

3.1. PIONEERING STUDIES

Dodge and Cline (1901) and Dodge (1917) first studied the dynamics of saccadic movements. Using the corneal reflexion recording photographic technique, they found that MV, PV, and saccadic duration increase with saccadic amplitude. They also noted

function of objective task characteristics and it is one of the most essential factors affecting task performance. Frequently, ***mental workload (or cognitive load)*** is the term used to describe the mental cost of accomplishing the task demands (Wickens 1984; 2002; Wickens & McCarley 2008) i.e. the individual reaction to these objective requirements. Although the terms ‘mental workload’ and ‘cognitive load’ are used interchangeably, they are not identical (for a discussion, see Sweller et al. 1998). Nevertheless, for the purposes of this paper we will use the expressions as synonym. Fluctuations of attentional state are also modulated by cognitive load (Tomasi et al., 2007), i.e. the allocation of mental resources (attention), is hinged to the different levels of mental workload (Wickens & Hollands, 2000). Recently it has been shown that an increase of cognitive load involves increased attentional processing (Tomasi et al., 2007). Finally, ***mental fatigue*** is defined as a ‘‘state of reduced mental alertness that impairs performance” (Grandjean, 1980) and refers “to the effects that people experience following the course of prolonged periods of demanding cognitive activity, requiring sustained mental efficiency” (Lorist et al., 2005).

that saccade generation was influenced not only by muscular fatigue, but also by mental fatigue and the subject's state of arousal.

Later studies replicated these early results and moreover showed that changes in alertness (induced by alcohol, sedative substances, and natural drowsy states) all result in slower eye movements (Becker and Fuchs, 1969).

Bahill and Stark (1975) and Schmidt et al. (1979) confirmed Dodge's observation that decreases in saccadic velocity (MV and PV) are not due exclusively to muscular fatigue, but they arise partly from defective processes at the level of the saccadic coordination system. Around the same time, Bahill et al. (1975) introduced the main sequence analysis, which further revealed the relationships between the various saccade parameters. In normal subjects, saccade amplitude and saccadic duration are related in a fairly linear fashion (Bahill et al., 1975). The relationship between the saccade amplitude and PV is linear only for saccades smaller than 20º (Leigh and Zee, 1999; Collewijn et al., 1988).

The above findings remained controversial for several decades (e.g.: Boghen et al., 1974) due to a lack of consistency in recording techniques, methodology and differing saccadic magnitude ranges. The great potential of saccadic velocity as an attentional index became apparent only after Galley's comprehensive review (Galley, 1989) summarized the most important causes of variability in saccadic velocity and concluded that "saccadic eye velocity is probably a more sensitive measure of alertness than most other parameters commonly used" (Ron et al., 1972). Here we review the experimental evidence supporting Galley's conclusion, and its validity today.

3.2. GALLEY' CONTRIBUTIONS

Several of Niels Galley's studies are worth mentioning in light of their relevance to applied and basic research on saccadic dynamics (Galley, 1993, 1998, Galley & Andrès 1996, Schleicher et al., 2008). Galley (1998) measured PV as an indicator of attentional activation during a tracking task with different stimuli frequencies, a classic study that has been neglected in a number of recent reviews of the field (for example: Morad et al., 2009 or Hirvoen et al., 2010). Galley (1993) and Galley and Andrès (1996) first investigated the variation in saccadic dynamics as an index of attentional state in ecological conditions (i.e. driving a car), in which eye movements have direct consequences on task performance.

To understand the importance of these experiments, we must delineate first the most common limitations of saccade research. Most investigations to date have studied saccadic behaviour in tasks where the oculomotor performance is dissociated from the natural role of the saccades, which is to make crucial perceptual information rapidly available for high resolution inspection (Montagnini & Chelazzi 2005). For example, experimental tasks often fail to represent natural oculomotor behaviour (Edelman et al., 2006), such as the antisaccadic task (e.g. App & Debus, 1998; Zils et al., 2005), in which subjects are required to direct their gaze to the opposite side of a visual target presented on a computer screen (thus producing an antisaccadic movement).

Galley (1993) aimed to evaluate the sensitivity of the electrooculogram [EOG] to measure the gaze behaviour of subjects driving a car. Among other eye-related parameters it was recorded MV, during different simulated conditions. The results showed a decrease in the MW values as the subjects' time-on-task (i.e. the time the subjects spent actively engaged in the task) increased (signalling an increase in mental fatigue). Galley concluded that MV could be a sensitive index of the driver's attentional state. One potential caveat of this study was that the specific tasks used (different secondary tasks) might have produced artificial driving behaviour.

Galley and Andrès (1996) later overcame the limitations of Galley's 1993 study. They investigated the effect of long-term driving (drowsiness) in natural conditions, in the absence of a secondary task. Participants drove at least 6 hours per day during 5 days. The experiments manipulated three main factors: road environment (city vs. motorway), subject's tiredness (time-on-task: five one-hour blocks), and alcohol consumption (0 mg vs. < 0.5 mg), and used saccadic parameters to indicate changes in information processing. The effects of city vs. motorway and of vigilance (time-on-task and alcohol intake) were significant. Increased information processing during city driving led to higher MV than during motorway driving, and decreased vigilance resulted in moderately lower MV.

Both Galley (1993) and Galley and Andrès (1996) measured MV rather than PV, and used a standardization procedure to eliminate the influence of changing amplitudes on saccadic duration and velocity (Galley, 1989). This procedure standardizes the MV and duration values using the formula: "Standardized value = 100 * (measured value / expected value for this amplitude)" (see Schleicher et al., 2008 for more details).

3.3. RECENT WORKS

The above studies concluded that alterations in attentional states, such as those induced by mental fatigue and arousal, can be reflected in changes in PV and/or MV. Bahill and Stark (1975 a) concluded that saccadic eye movements are useful indicators of psychological state for people performing real tasks, and pointed out their great potential utility for psychologists and human factors engineers. Recent studies have not followed up on Bahill and Stark's suggestion, however (Parasuraman and Rizzo 2007, Schleicher et al., 2008).

Saccadic dynamics, and particularly PV, may have failed to gain traction as attentional state indices in applied ergonomics due to the technical and methodological difficulties involved with their measurement, especially in naturalistic settings. Traditionally, cognitive ergonomists and risk management experts have tended to use subjective tests and questionnaires that are relatively easy to administer and to interpret (for example: Cooper and Harper 1969). The first main sequence studies were moreover published in engineering or physics journals (i.e. Mathematical Biosciences, Bahill et al., 1975) not generally read by psychologists and human factor experts. Such limitations have been largely overcome in recent years thanks to the availalability of user-friendly commercial eye-trackers, usually based on high speed video recordings of the eye from cameras located on a lightweight headband or positioned in front of the operator. Data are collected unobtrusively without the need for intensive specific academic or technical training. The next sections summarize the recent results from three different application areas: a) Clinical, b) Military, and c) Everyday life.

3.3.1. CLINICAL DOMAIN

Bahill and Stark (1975 a) anticipated that saccade dynamics could become a common clinical diagnostic tool for specific or general diseases. Recent studies have measured the PV of prosaccades (saccades directed towards a target) and antisaccades to examine deficits associated with alterations of the frontal areas involved in programming saccadic movements (Garbutt et al., 2001).

Winograd-Gurvich and colleagues (2006) studied the ocular motor differences between patients with major depressive disorder. The author found that PV increases, approximating to the main sequence rule (Bahill et al., 1975) in patients suffering from non-melancholic depression. Contrarily melancholic patients have difficulty to increase the PV (as function of the amplitude). The authors suggested the reduced PV in melancholic depression group could be explained by a dopamine dysfunction. In contrast the PV behaviour in non-melancholic patients could be a by-product of prefrontal cortex dysfunction reflecting changes in serotonin levels (perturbations in the serotonergic system are thought to underpin the non-melancholic symptoms of depression; Malhi et al., 2005). Remarkably, the administration of dexfenfluramine (a serotonin receptor agonist) significantly increased PV for relatively large saccade amplitudes (i.e. 15°) (Gijsman et al., 2002). Even though the mechanisms underlying the serotonin effects remain unclear (Winograd-Gurvich et al., 2006), Gijsman et al. (2002) suggested that PV may be mediated by large serotonergic axons, which project to regions including the superior colliculus and several brainstem nuclei.

Drugs active at the GABA/benzodiazepine receptor affect attention and cognitive activity (Barker et al., 2004; Stewart, 2005). Glue et al. (1991) examined the effects of α2-adrenoceptor agonists (clonidine) and antagonists (idazoxan) on saccadic eye movements, and found that they had direct effects on PV but not on other saccadic parameters, such as accuracy or latency. Clonidine, which generally causes sedation, was associated with PV decreases; idazoxan, which generally increases arousal, was associated with PV increases. Similar results were observed by Ball et al., (1991), demonstrating the effect of the midazolam (benzodiazepine receptor ligands) on PV. The study confirmed that PV is reduced in a dose-dependent manner by increasing doses of midazolam.

Grace and colleagues (2010) obtained similar results using EOG to measure lateral eye movements. They found that PV was a sensitive biomarker to detect the sedative interaction between opioid (morphine) and sleep deprivation in opioid-naive populations, showing a general decrease in PV values.

3.3.2. MILITARY DOMAIN

Non-invasive methods are being developed to monitor and detect mental impairment in soldiers to predict performance decrement and human error that might lead to catastrophic outcomes in operational environments (Friedl et al., 2007). Most of the published literature comes from military medical departments investigating saccadic velocity in relationship to mental fatigue (for example: Porcu et al., 1998; Russo et al., 2003; LeDuc et al., 2005; Rowland et al., 2005; Morad et al., 2009; Hirvonen et al., 2010). Such studies typically follow similar experimental designs (with some variations, such as the amount of nighttime sleepiness or the intervals between battery tests) and aim to evaluate the effect of sleep deprivation on saccadic behaviour and task performance.

Hirvonen et al.'s study (2010) was part of a larger research project that investigated the effect of sleep deprivation on performance in two high-speed navigation systems, and compared the sensitivity of EOG and the Fitness Impairment Test (FIT, Pulse Medical Instruments, Inc., Rockville, MD) to detect variations in PV. FIT is a self-contained, fully automated, computer-controlled, commercial optical recording system, which combines infrared pupillometry with eye movement tracking. A test session requires approximately 30/90 s. The system measures four variables: saccadic velocity*, pupil diameter, pupil constriction latency, and pupil constriction amplitude (Morad, 2009). Hirvonen et al. (2010) used a mobile FIT machine with 600 Hz sampling rate and 0.1 mm resolution. Subjects had to follow a green light that moved along the horizontal axis from left to right (a classical pro-saccadic task). Saccadic velocity was calculated as the average PV of four 20º saccades.

Eleven navigators of the Royal Norwegian Navy remained awake for 60 hours, performing vision tests and filling in subjective questionnaires (i.e.: Karolinska Sleepiness Scale, Åkerstedt & Gillberg, 1990) every 6 hours. The results showed that that PV progressively decreased as function of time-on-task, and that EOG measurements detected fatigue with more sensitivity than the FIT tool.

Russo et al. (2003), LeDuc et al. (2005), Rowland et al. (2005), and Morad et al. (2009), measured performance in pre/post operational activity, with a similar experimental design and also found decreased saccadic velocity with increased mental fatigue.

3.3.3. EVERYDAY LIFE DOMAIN

Early ergonomic studies used gaze measurements such as gaze duration or direction to assess operator mental state (for more details see Kramer and Parasuraman 2007). Few studies investigated the validity and sensitivity of PV and/or MV as an index of human attentional state in ecological tasks, however. Schleicher et al. (2008) applied Galley's original ideas (Galley 1993, Galley & Andrés 1996) to study changes in various oculomotor variables (including main sequence parameters and blinking behaviour,

* Most of the studies using the FIT tool report saccadic velocity values without specifying whether they indicate MV or PV. Further, the use of percentage values, instead of the original values expressed in deg/s, makes it impossible to deduce if the results refer to PV or MV.

measured by EOG) as a function of increasing sleepiness in a simulated traffic situation. Participants had to drive for two hours on a monotonous road circuit, without any secondary tasks. Blinking behaviour (blink duration, delay of lid reopening, blink interval and lid closure speed) was the best indicator of subjective (measured by the KSS), and objective (rating of facial behaviour) sleepiness. Among the dynamic saccade parameters (MV, amplitude and duration), only mean saccadic duration increased moderately with increasing sleepiness.

Di Stasi and colleagues (Di Stasi et al., 2010 a, c, d; Di Stasi et al., submitted a, b, d) investigated the validity of main sequence parameters (saccadic amplitude, duration, and PV) as attentional state indices in applied tasks (including air traffic control tasks, microworlds and driving simulations), that induced different attentional states. (Microworlds are simulations of real tasks that change dynamically and reproduce the important characteristics of real situations). The experiments combined performance, subjective, and psychophysiological measures to assess mental state (Brookhuis et al., 2008; Di Stasi et al., 2009). Eye positions were tracked with EyeLink (SR Research, 500 Hz), and PV was analyzed as a function of saccade length via saccadic-bin analysis.

The saccadic-bin analysis represents a different and valid approach compared to the classical standardization procedure (see section 3.2. Galley' contributions) formalized by Schleicher et al. (2008) because it is not necessary to perform any corrective procedure on the collected data or to operate any comparison between the participants measured values and normative ones.

Di Stasi et al. (submitted c) showed the potential of PV as a vigilance screening tool (i.e. an online real time measure of mental fatigue) in drivers. Subjects performed a making-saccade task immediately before and after a 2-hour long driving task. Subjective questionnaires (Stanford Sleepiness Scale [SSS, (Hoddes et al., 1973)] and Chalder Fatigue Scale [CFS, (Chalder et al., 1993)] were administered immediately before and after the driving task. Scores on the SSS and CFS were significantly higher after the driving task. The duration of saccades larger than 10° increased from the first to the second measuring time, and PV of saccades larger than 7.5° decreased. The data recorded during the driving task presented the same tendency: a gradual decrement of PV after the first hour of driving. The authors concluded that PV is a valid index of mental fatigue changes during long and repetitive tasks.

Di Stasi et al. (2010 c) studied the effect of task complexity on the main sequence. The experiment required multitasking performance in a simulated air traffic control setting. Participants performed two contemporary tasks that demanded different perceptual and central processing resources: a button decision task with the non-writing hand and a paper-and-pencil task with the writing hand (Wickens 1984; 2002; 2008). The experimental conditions induced different workload levels (confirmed by subjective ratings (using a mental workload test [MWT] (Di Stasi et al., 2009)) and behavioural results (number of response errors and delayed answers)), and PV values, with lower PVs during high-complexity tasks. Unclear effects were found on saccade duration and MV. One potential caveat of this study is that the experimental design did not allow distinguishing between the effects of task complexity and time-on-task.

Di Stasi et al. (submitted a) overcame the above limitation. The study used the Firechief (Omodei & Wearing, 1995) incident simulator (microworld) as a complex and dynamic problem-solving task. The visual configuration of the screen differed between groups to create two different levels of task complexity. Time-on-task was also manipulated (within groups). The experiments aimed to compare the validity and sensitivity of PV with those of performance and subjective ratings. PV was a more sensitive index of task complexity (mental workload) and time-on-task (mental fatigue) than either performance (system scores) or subjective measures (MWT, see above). Saccade duration and MV were not affected by task complexity or time-on-task. Consistent with previous studies, PV decreased with increased task complexity and longer time-on-task (i.e. higher level of mental fatigue).

Di Stasi and colleagues (Di Stasi et al., 2010 d) further demonstrated that PV is sensitive to variations in task complexity during short driving tasks (again, PV decreased as the task complexity increased). Saccade duration and MV were not affected by task complexity. The experiment manipulated time-on-task (mental fatigue) independently from task complexity (mental workload). Unlike mental workload, mental fatigue (over a 45 minute time period) had no effects on the main sequence.

The studies above indicate that both task complexity and time-on-task (if exceeding approximately 60 minutes) affect saccade generation, lowering the saccadic PV.

4. DISCUSSION

The cerebral cortex and the brainstem are part of the visual-saccadic system. The frontal cortical oculomotor area (which includes the frontal eye fields, supplementary eye field, and dorsolateral prefrontal cortex) plays a central role in the top-down control of saccades (Munoz & Everling, 2004).

The effects of attentional state on main sequence parameters such as PV may arise at a late stage of oculomotor processing (i.e. at the level of the excitatory burst neurons, whose firing rates encode the velocity signal of saccades (Zils et al. 2005)). Munoz and Everling (2004) proposed that increased/decreased attentional processing can affect the strength of the excitatory connections from the frontal cortex to the brainstem reticular formation, thus modifying the characteristics of the main sequence. Thus changes in PV could reflect modulations in the activity of the reticular formation (such as the synchronization of firing times).

Following from Munoz and Everling's model (2004), the effect of mental fatigue on PV (for example see: LeDuc et al., 2005; Morad et al., 2009; Hirvonen et al., 2010, Di Stasi et al., 2010 d), may be explained by the involvement of sleep-regulating centers (i.e. caudate nucleus, thalamus, globus pallidus external, substantia nigra, and substantia nigra pars reticulate) on the reticular formation). Straube and colleagues (1997) showed that saccadic performance dropped (saccadic latency increased and saccadic accuracy and PV decreased) when rhesus monkeys performed a task in the dark (compared to performance of the same task in dim light). The authors proposed that dim lighting prevented changes in cortical inputs signals to superior colliculus (or cerebellar input signals to the brain stem) by evoking more sustained activation of the cortical areas involved in the orientation of attention (Posner & Petersen, 1990). It is important to note that most of the experiments discussed in this review were conducted in darkened laboratory conditions (for example: De Gennaro et al., 2000 or Hirvonen et al., 2010); thus is possible that the PV impairment observed in long duration experiments is related to the activation of the brain's sleep centers.

In summary, task complexity, mental fatigue, and diseases of the central nervous system can result in impaired PV (figure 3), perhaps due to deficient synchronization and/or reduced firing rate of the saccadic burst neurons of the brainstem's reticular formation (Galley, 1989).

5. CONCLUDING REMARKS

More than 100 years of investigation have generally supported Dodge's (1917) hypothesis that that decreases in saccadic velocity (MV and PV) are partly due to defective processes at the level of the saccadic coordination system. Our analysis of the literature to date supports the conclusion that PV is a promising index of variations in human attentional demand, with important potential applications in applied ergonomics and in the clinic. Galley's early studies (1989; 1998) and recent work by other groups (for example: Hirvoen et al., 2010, Grace at al., 2010), show that saccadic dynamics are affected by changes in mental state. This valuable starting point should encourage further research to uncover how variations in cognitive processing demands affect saccade dynamics during applied tasks in everyday life (ranging from call centers to air traffic control towers).

Recent research has begun to address how attentional fluctuations impact the dynamics of microsaccades (small involuntary saccades that occur during attempted fixation, see Martinez-Conde et al., 2009 or Rolf, 2009 for reviews). A few studies (Otero-Millan et al., 2008, using free-viewing and visual search tasks; Laubrock et al., 2005, using an attention cueing task) have started to investigate the effects of task complexity and cognitive load on microsaccade parameters. Their initial results suggest that microsaccade production increases with cognitive demand (Laubrock et al., 2005; Otero-Millan et al., 2008; but see Pastukhov and Braun, 2010). Future applied research should combine the analysis of micro- and macro- saccades in ecological contexts. Such research may prove very fruitful: operators using video display terminals need to scan reduced areas of interest (approximately 20º in size) and as a consequence generate smaller magnitude saccades (see Di Stasi et al., 2010 c).

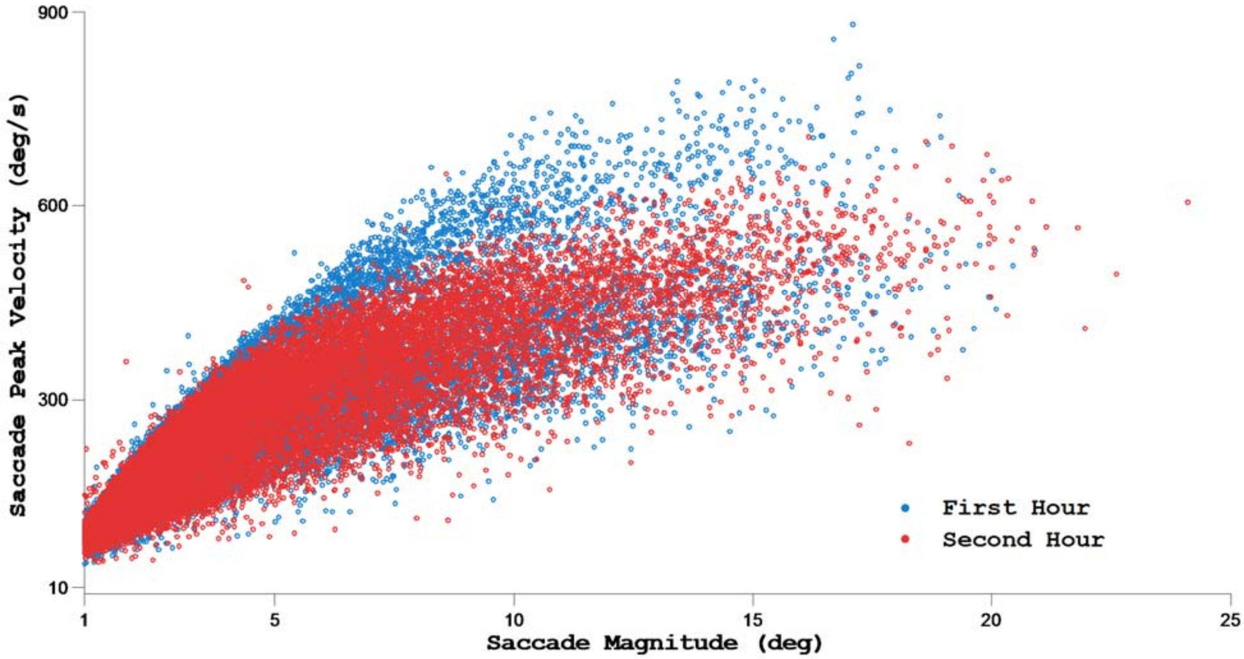

Figure 3. Effect of fatigue on PV.

Eight participants performed a visual searching task for two hours. Blue dots represent the saccades produced during the first hour [Amplitude (X= 4.88; SD= +/- 3.42); PV (X=267.13; SD=+/- 131.97)] and red dots indicate the saccades produced in the second hour [Amplitude (X= 5.13; SD= +/- 3.66); PV (X=264.08, SD= +/- 123.26)]. Approximately 16335 saccades were produced in each hour.

6. FUTURE STEPS

In our information technology society there is a crucial need to evaluate the behaviour and cognitive efforts of users interacting with artefacts in real time. It remains a big challenge to determine the most helpful type and level of automated assistance for operators/users/drivers (e.g. Langan-Fox et al., 2009); showing that PV is a valid and sensitive index to detect mental variations in complex and real conditions is only a small part of the answer. Foreseeing that “the vehicles of the future will be equipped with a cognitive prosthesis…” (cit. Cacciabue & Carsten, 2010), the next step will be to create systems with the ability to identify the operator’s mental state from physiological data. The ability to identify changes in attentional state in real time could help design systems that would allocate tasks to operator and/or machine in an optimal and dynamic way (e.g. Kaber et al., 2006).

Importantly, these objectives must be achieved without interfering with the task or compromising its safety. The automotive industry is among the most productive industrial sectors concerned with this issue (see for example: AIDE, 2005; ISi-PADAS, 2007, ITERATE, 2009). Numerous studies on intelligent transport systems have focused on the topic of safety over the last two decades (e.g. Piao and McDonald, 2008), with recent studies addressing the effects of the temporal and physical features of warning systems on driver performance and attitudes (e.g. Wiese & Lee, 2004; Cacciabue, 2007). Preliminary results are beginning to reduce this current gap in knowledge (e.g. Jou et al., 2009 or Di Stasi et al., 2010 a, b; Di Stasi et al., submitted b).

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MAIN PUBLICATIONS

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