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

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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 (between groups) and the amount of training (within groups). 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 and 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 load1) 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 and 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 and 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 the saccadic main sequence as an alternative measure to the classical psychophysiological measures (i.e. heart
rate, electrodermal activity or electroencephalographic activity, see Parasuraman and 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 and Myung, 2005). The human eyes are outgrowths of the brain and are considered as part of the central nervous system (Hoar, 1982; Wilson and 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 and 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 and Friedman-Berg, 2006; Schleicher et al., 2008; Dey and 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., 2008).

Saccadic eye movements vary in amplitude, duration, and (peak) velocity (Dodge and 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 mean 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, 2010a, 2010b).

Di Stasi et al. (2009) evaluated whether measures of eye activity correlated with MW and different types of risky behavior 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. (2010b) 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. (2010a) 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 behavioral 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 (EyeLink 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., 2011, 2010a, 2010b), 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 databases. 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 orbital 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 and 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 and 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 (in this case induced by manipulating the screen configuration) 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).

To reach this aim, the selected screen configurations of FireChief (low/high demanding see below) have been created after performing two pre-experiments.

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 gender variable 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 and Stateland, 1988) and the Workload Profile (Tsang and Velazquez, 1996). The instrument asked participants to make an evaluation of 13 factors. Each factor was presented as a visual analog 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 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 0.1° with a minimum velocity of 30° s⁻¹ and a minimum acceleration of 8000° s⁻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 and Wearing, 1995). 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 and Dörner, 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. 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) and current performance score.

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]

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. Each element contributed to the visual complexity of the screens but subjects were asked to focus on three central elements: fire spots, 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 center 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 meantime 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 ms) and faster response times in the Centre/Grouped/Brown condition (M = 4157 ms), F(1, 23) = 27.18; p < .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, p < .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. Fig. 1 shows the final screen configurations selected for our experiment.

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 s each), during which the experimenter checked (supervising the interaction behavior 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 s and the study session ended after approximately 1 h and 30 min.

2.6. Design

The experiment followed a $2 \times (2)$ mixed factorial design, with Screen Configuration as a between-participants variable (low vs. high demanding), and Training (1st vs. 10th 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 $2 \times 2$ Training (1st vs. 10th Trial, within subjects) analysis of variance (ANOVA). No significant effects were found (all $F$s < 1, see Table 1).

3.2. Performance scores

For the performance mean scores, a $2 \times 2$ Training (1st vs. 10th Trial, within subjects) ANOVA was run. Six subjects were excluded from this analysis because of log-system failures during the experimental recording.

| Table 1 | Overview of the experimental results: subjective results, performances scores, and psychophysiological data [saccadic peak velocity (°/sec)]. The results (average and standard deviation values) 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       |
| Subjective data, mean score (SD) | 50.51 (9.26) 51.21 (12.25) 52.32 (7.71) 51.45 (10.44) | 50.51 (9.26) 51.21 (12.25) 52.32 (7.71) 51.45 (10.44) |
| Performance data, mean score (SD) | 67.7 (11.50) 80.3 (14.81) 67.9 (9.83) 84.6 (12.97) | 67.7 (11.50) 80.3 (14.81) 67.9 (9.83) 84.6 (12.97) |
| Psychophysiological data, mean PV (SD) | 296.01 (32.41) 285.60 (22.27) 279.08 (24.14) 274.49 (21.49) | 296.01 (32.41) 285.60 (22.27) 279.08 (24.14) 274.49 (21.49) |

Fig. 2. Illustration of the interaction between Screen Configuration × Training × Saccade Length factors. Vertical bars denote 0.95 confidence intervals.
A main effect was found for Training, \( F(1, 38) = 50.31, p < .001, \) but neither for Screen Configuration \( [F = 0.47] \) nor for interaction \( [F = 1.05] \). During the last trial, participants performed better than the first one, showing the effects of the training (see Table 1).

### 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 0.01° to 13.9° were created (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°). Following this binning procedure (Di Stasi et al., 2011, 2010a, 2010b), the resulting medians of PV were submitted into 2 (Screen Configuration, between subjects) \( \times 2 \) Training (1st vs. 10th Trial, within subjects) \( \times 8 \) (Saccade Length, within subjects) and ANOVA were calculated.

The Screen Configuration factor showed a significant effect, \( F(1, 44) = 4.11, p < .05 \). 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, \( F(1, 44) = 5.81, p < .05 \). PV in the last trial was lower than it was in the first trial (see Table 1). As hypothesized, higher PV were found with increasing saccade length \( F(7, 308) = 2685.7, p < .001 \) (the main sequence rule, see Fig. 2). The interaction Screen Configuration \( \times \) Saccade Length, Training \( \times \) Saccade Length, and Screen Configuration \( \times \) Training \( \times \) Saccade Length also revealed significant effects \( F(7, 308) = 22.21, p < .05 \), \( F(7, 308) = 2.93, p < .05 \) and \( F(7, 308) = 22.27, p < .05 \), respectively. The interaction Screen configuration \( \times \) Training was nonsignificant \( F < 1 \).

We next analyzed the Screen Configuration \( \times \) Training \( \times \) Saccade Length interaction, separating the 1st vs. 10th trials (see Fig. 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 \( t = 2.03, p < .05 \)]. The 10th Trial showed the same effect, but only in the 3rd and 4th bin [minimum value of \( t = 2.27, p < .05 \)]. From these results it might be concluded that the influence of task complexity upon the relationship between training and saccade length has been modulated by another intervening factor: the time on task, i.e. mental fatigue (for more details see Discussion and conclusions).

### 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 et al., 2009).

The main aim of this experiment was to analyze the sensitivity of saccadic 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 for publication) as well as between performance and user estimates of performance and MW (Yeh and 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., 2010a, 2010b), 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 and 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 major 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 saccadic dynamics. In our experiment, task complexity (or MW experienced by the participants) impaired the PV (no effect was found on saccadic duration or mean velocity, 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 behavioral 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 behavior 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 h 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 et al. (1979), Galley (1989), or with our latest results (Di Stasi et al., submitted for publication). 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 h 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. non-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 min 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 (Fitts, 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.

Third, because the results of this study are based on pure behavioral measures, the plausible proposed neurophysiologic explanation needs to be confirmed in future studies.

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., 2010b). While using video display terminals, the operator is screening a reduced area of interest (approximately 20°) and as a consequence generates smaller magnitude saccades (see Di Stasi et al., 2010a). For this reason the analysis of very small saccade, including fixational eye movements (saccade < 1°), could represent an optimal alternative solution. Recently, much progress has been made in understanding the behavior of these small saccades (called microsaccades) during the fluctuation of attentional state (see Martinez-Conde et al., 2009 or Rolfs, 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 behavior (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 and 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 behavior (Di Stasi et al., 2009), simulated driving performance (Di Stasi et al., submitted for publication), and air traffic controller simulated setting (Di Stasi et al., 2010a). In line with the original results of Galley (1989, 1998) and with several modern investigations (for example Hirvonen 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 saccadic dynamics during real work condition.

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