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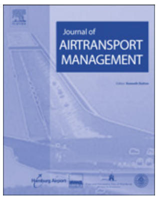

Note

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

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ABSTRACT

To assess the effects of workload pressures, participants interacted with a modified version of air traffic control 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 is used as a theoretical reference framework. Saccadic peak velocity decreases with increasing cognitive load, in agreement with subjective test scores and performance data. That saccadic peak velocity is sensitive to variations in mental workload during ecologically valid tasks is demonstrated.

1. Introduction

“Controller workload is likely to remain the single greatest functional limitation on the capacity of the ATM system” (Eurocontrol, 2004). Evolution of air traffic management (ATM) in the 20th century led to changes in the role of the air traffic controller (ATC) (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 and Caggiano, 2002) and is considered a limiting factor regarding ATM expansion. 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 and Friedman-Berg, 2006). There are, however, some problems related to these indices that make them difficult to use in the dynamic and complex tasks encountered in real workplaces.

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 and Debus, 1998). These variations can be independent of amplitude. Recent findings (LeDuc et al., 2005; Di Stasi et al., 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.

2. Method

2.1. Participants

Twenty-three volunteers (nine males) took part in this experiment; their mean age was 24.6 years with a standard deviation of 3.65 years. 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.

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 $30^{\circ}\mathrm{s}^{-1}$ and a minimum acceleration of $8000^{\circ}\mathrm{s}^{-2}$, maintained for at least 4 ms. A 13-point calibration and validation was performed before

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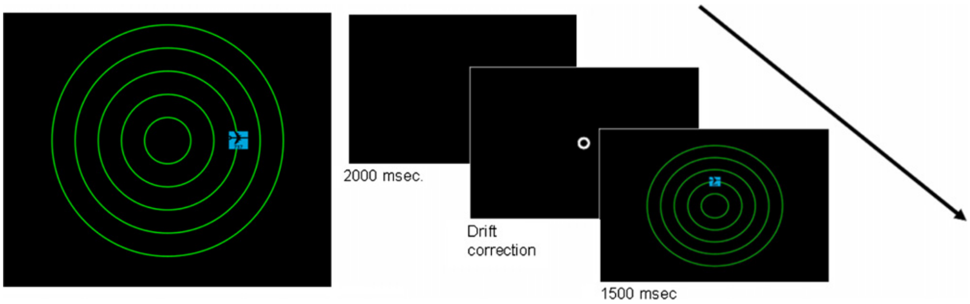

Fig. 1. Sample screenshot taken from the experimental environment.

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 ms and 10 ms 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 within 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°).

Forty 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°.

2.3. Design

Three 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 (ms), saccadic velocity (degree of visual angle/s) and PV (degree of visual angle/s). 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 sheet were constructed by adding five to each 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).

The mean scores of the MWT scales were submitted to a three (task complexity: low, medium and high) repeated-measures

Table 1
Overview of the experimental results ($^*p < 0.05$).

	Low complexity	Medium complexity	High complexity
*MWT (score)	36.187	41.956	47.525
*Error (number)	3.174	1.565	0.913
*Delayed answers (number)	2	5.391	7.870
Saccadic duration (ms)	30.254	29.764	30.036
Saccadic velocity (visual deg/s)	112.521	113.790	112.088
*PV (visual deg/s)	215.884	212.152	209.162

Note: For MWT scores, error and delayed answer mean values were considered. Median values were considered for mean sequence parameters.

analysis of variance (ANOVA). Significant effects were observed for task complexity, confirming that the experienced mental workload changed in concordance with the experimental manipulation (see Table 1).

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 the repeated factor. As expected, we obtained a reliable difference in the number of errors between the three complexity levels. Planned comparisons of means revealed significant differences in the number of errors between low task complexity and medium/high task complexity (see Table 1). Similarly, the number of delayed answers were computed and statistically tested. Results showed a significant increase in the number of delayed answers with increasing task complexity. Planned comparisons of means revealed significant differences in the number of delayed answers between low/medium task complexity and high task complexity.

In the next step we analyzed the sensitivity of saccadic main sequence parameters in relation to changes in mental workload. Saccade amplitude was categorized into five bins (saccade length), ranging from 0.001° to 7.5° (0.001°<°bin 1 < 1.5°, 1.5°<°bin 2 < 3.0°, 3.0°<°bin 3 < 4.5°, 4.5°<°bin 4 < 6.0°, 6.0°<°bin 5 < 7.5°). Three repeated-measures three (task complexity) times five (saccade length) ANOVAs were calculated for median values of saccade duration, velocity and PV. Analysis of eye movements was carried out for 22 participants; one subject was excluded because of missing data.

Analysis of saccade duration revealed a significant main effect of saccade length but not of task complexity. The interaction had a significant effect. Similar results were observed for saccade velocity. Again the analysis revealed significant effects of saccade length but not of task complexity, and the interaction had a significant effect. Analysis for PV showed the main effects of saccade length and of task complexity, but no interaction was found. Planned comparisons of mean values revealed significant differences between low- and high-task complexity.

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 (Fig. 2). This can be explained by 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 (0.001°–7.5°) it is possible that the mathematical relation between these parameters could mask the effect of our main manipulation.

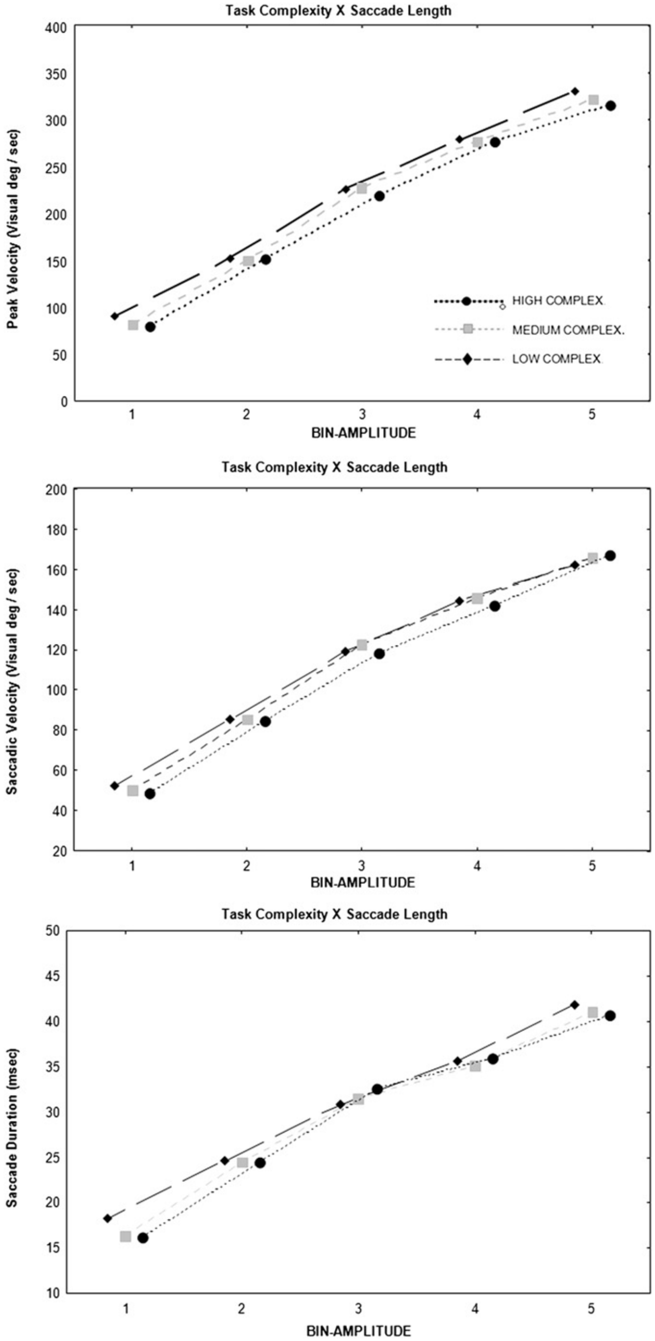

Fig. 2. Illustration of the interaction between task complexity and bin-amplitude factor on the main sequence parameters.

4. Discussion

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 and 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.

We obtain different levels of mental workload in a complex, ecologically valid environment. Results obtained from subjective ratings confirmed that combining different task complexities could 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 and decreased with increasing task complexity, whereas the number of delayed answers increased in parallel with the task complexity due to an increase in time pressure. Results obtained from the subjective ratings and behavioural measures (number of errors and delayed answers) confirmed that combining these types of secondary tasks with task complexity manipulation could be a fruitful strategy for inducing different mental workload levels. On the basis of these results, we investigated all parameters of the saccadic main sequence (duration, velocity and PV) with respect to mental workload levels. We found an effect of task complexity only for PV only.

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