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Evaluating mental workload while interacting with computer-generated artificial environments

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The need to evaluate user behaviour and cognitive efforts when interacting with complex simulations plays a crucial role in many information and communications technologies. The aim of this paper is to propose the use of eye-related measures as indices of mental workload in complex tasks. An experiment was conducted using the FireChief® microworld in which user mental workload was manipulated by changing the interaction strategy required to perform a common task. There were significant effects of the attentional state of users on visual scanning behavior. Longer fixations were found for the more demanding strategy, slower saccades were found as the time-on-task increased, and pupil diameter decreased when an environmental change was introduced. Questionnaire and performance data converged with the psychophysiological ones. These results provide additional empirical support for the ability of some eye-related indices to discriminate variations in the attentional state of the user in visual–dynamic complex tasks and show their potential diagnostic capacity in the field of applied ergonomics.

1. Introduction

Funke [1] defined a complex problem-solving situation as a system governed by a set of interrelated variables such that: its internal dynamics are opaque, and the system is difficult to control because of the inapplicability of simple mechanisms for resolving problems. In this sense, microworlds are computer-generated artificial environments that are complex (have a goal structure), dynamic, and opaque (the operator must make inferences about the system) [2]. The state of the problem changes autonomously and as a consequence of the actions of the subject, and decisions must be made in real time. Microworlds can reproduce important characteristics of different situations while still allowing the possibility of manipulation and experimental control. Researchers have used microworld tasks to study ergonomic topics such as process control [3], extended spaceflight [4], internet shopping [5], submarine warfare [6], and fighting forest fires [7–9,10]. In all the above-cited works, researchers wanted their subjects to act ‘naturally’, as they would in the real world, to solve these problems. The subjects’ strategy differences used to solve these tasks should be reflected in the mental workload experienced by the participants.

1.1. Mental workload in problem solving strategies

Mental workload (MW) has long been recognized as an important factor in human performance in complex interactive systems and has been defined as the amount of cognitive capacity required to perform a given task [11]. It therefore refers to “a composite brain state or set of states that mediates human performance of perceptual, cognitive, and motor tasks” [12].

When a person is learning how to perform a complex and dynamic problem solving task, there is a high demand for processing resources. These demands diminish through learning and thanks to automation processes developing appropriate problem solving strategies [8,9].

A problem-solving strategy is a sequence of operations used to search through a solution space [13], or better said, a pattern of actions or decisions that a person repeats during the performance of a task that defines the style used to face it. Therefore, the development of strategies is a process that: (1) favors the reduction of the cognitive resources needed to solve the task; (2) eliminates some of the decisions necessary to perform it; and (3) speeds up performance. Once a person has developed and refined the use of a strategy, it is put into practice every time the task is performed [9]. These ideas were summarized by Anderson [14] and later by Rasmussen’s studies [15,16]. Anderson [14] considered the acquisition of cognitive strategies to deal with task complexity as one of the most important dimensions of learning. In his model, acquisition of cognitive strategies is related to the automatization of a cognitive ability. When part of a cognitive skill is automated, its

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performance requires less cognitive effort, so that the cognitive system can focus on other problematic aspects of the ability. Therefore, as learning is more extensive, fewer resources are necessary for the task due to automatization [17]. On the same line of thought, Rasmussen [15,16] proposed a theory on the control of action based on the existence of several levels of processing, to explain how different levels of cognitive control are exerted in human behaviors. These levels of cognitive control could be used to predict the automation processes in human-computer interaction. The three levels of control that Rasmussen proposed are: (i) a level based on abilities, for activities that are performed automatically; (ii) a level based on rules, for well-known situations in which experience provides us with a response that has proven successful; and (iii) a level based on knowledge, for new situations in which there are no rules and a different response must be planned. The control level reached will depend on the familiarity a person has with the situation, or on the quantity of training that the person has had in the task. As a consequence of Rasmussen's proposal, practice would lead to a use of more automatic activities based on the levels of rules and abilities. Following Rasmussen's intuition [15,16], if training takes place under variable conditions, the person will have fewer possibilities to practice the same strategy. The uncertainty about the environment would force continuous modification of strategy and would require attending to any change that might take place. Because of this, it would become more difficult to automate and consolidate the strategies. On the other hand, if the conditions and quality of the training remained stable, the possibility of repeating the same actions would be facilitated.

In our previous work using the FireChief incident simulator [9] we demonstrated that the automation and strategies could be manipulated by the type of training received, facilitating or hindering the consolidation of particular interactions [9]. In the present study we used a constant training to favor the consolidation of a particular strategy (fire control strategy [FS] vs. water strategy [WS]; see Section 2.2.4 for more details), therefore favoring automation and the loss of conscious control of the task. Once these strategies had been well trained (through 16 trials), an environmental change (wind direction) was introduced (in the last four trials). Our intuition was that this change will lead to an increase of mental workload for the FS group without affecting the WS group. If the user can know and perfectly predict how the task will develop, she/he will need an extra planning cost (more cognitive effort) to rearrange the interaction strategy after the change, in order to maintain an acceptable level of performance. We propose the use of eye-related indices as sensitive and valid indices to track and evaluate user MW during the interaction.

1.2. Eye-related indices as an assessment of user strategy

Mental workload has primarily been measured using subjective tests [18]. 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 MW. They have the advantage of being relatively easy to administer and to interpret, and they do not require extensive training or expensive equipment. However, one of the main problems with this technique is their off-line nature, which often makes them impractical or intrusive; for example, when control operators are asked to fill in MW questionnaires off-duty [18].

For the above caveat, researchers have turned their attention to neuroergonomic indices [19]. Among these indices (for example, functional magnetic resonance imaging and electroencephalography) and thanks to the development of new technological devices, the eye tracking method, as an indicator of user mental workload, has received a lot of attention (for more details see [18]). Ocular movements are often studied to understand perceptual-cognitive processes and strategies mediating performance in complex tasks [19]. The basic assumption is that brain activity offers the best estimation of user attentional state and, and since the eye is an extension of the brain [20], ocular indices can reflect changes in mental activity caused by the task being performed. One strength of using eye tracking methodology is that it also allows assessment of user strategy at the computer interface [21].

With this in mind, we explored visual scanning behavior (fixation duration and saccadic dynamics) and pupil diameter, as an alternative to MW questionnaires, while participants were interacting with the FireChief incident simulator. Recent studies have confirmed that visual scanning behavior and pupil diameter variation are sensitive to MW fluctuations [22]. In the above study, the authors examined the MW of participants while navigating an e-commerce website with two different searching tasks (goal-oriented shopping and experiential shopping), with each demanding different amounts of cognitive resources. A multidimensional approach including: subjective, behavioural, and psychophysiological indices, was used. In this study, visual scanning behavior and pupil diameter coincided with subjective test scores and performance data, showing a higher MW for 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 visual planning exploration. On the other hand, in goal-oriented shopping, the level of arousal is higher (due to task complexity and time pressure) so decision making is more difficult, and information stimuli attract the eyes so there is more distraction. In this situation, bottom-up processes play a main role in planning fixation behaviour, as shown by the higher number and shorter duration of fixations. Using the same methodological approach, the authors were able to prove the sensitivity of saccadic dynamic eye movement parameters (i.e. the amplitude and peak velocity [PV] of a saccade) during user interactions in dynamic and complex tasks, such as driving [23], riding [24], and performing several air traffic controller tasks [25]. Briefly, the above investigations [23–25] found an inverse relation between task complexity and PV, i.e. a decrease of PV with an increase in mental workload. These results, combined with the original observations in [26–28] suggest that saccadic dynamics are influenced by human attentional state.

The aim of the present study was to investigate whether eye related variables (fixation duration, pupil diameter, and PV) reflect MW differences in a situation where the characteristics of the interaction changed with the simulation (maintaining the same stimulus configuration) and required different amounts of cognitive resources. We expected that the FS would be more cognitively demanding, reflecting the perceptual visual task demands plus the extra cost from the planning needed to perform the task. This extra-cost will become more clear as the environment changed (in the case of a change in wind direction, see Section 2.4), because of the need to review the situation and possibly alter the location of the control fire. On the contrary, the WS will not require this extra planning or shift in strategy.

2. Methods

2.1. Design

The entire experiment followed a 2 × 20 mixed factorial design, with strategy as a between-participants variable (WS and FS), and training (20 levels) as a within-participants variable. Data were analyzed according to a 2 (strategy) × 5 (trials, last five levels of training variable) design.