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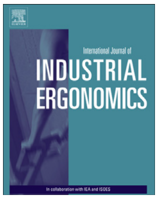

Air traffic control: Ocular metrics reflect cognitive complexity

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ABSTRACT

The objective of the study was to evaluate effects of complexity on cognitive workload in a simulated air traffic control conflict detection task by means of eye movements recording. We manipulated two complexity factors, convergence angle and aircrafts minimum distance at closest approach, in a multidimensional workload assessment method based on psychophysiological, performance, and subjective measures. Conflict trials resulted more complex and time-consuming than no conflicts, requiring more frequent fixations and saccades. Moreover, large saccades showed reduced burst power with higher task complexity. A motion-based and a ratio-based strategy were suggested for conflicts and no conflicts on the basis of ocular metrics analysis: aircrafts differential speed and distance to convergence point at trial start were considered determinant for strategy adoption.

Relevance to industry: Eye metrics measurement for online workload assessment enhances better identification of workload-inducing scenarios and adopted strategy for traffic management. System design, as well as air traffic control operators training programs, might benefit from on line workload measurement.

1. Introduction

According to the International Civil Aviation Organization (ICAO) medium-term passenger traffic is expected to increase by 6.3% in 2015 (ICAO, 2012) and air traffic control (ATC) is going to be one of the most affected activities of the whole air transport system. ATC is a service offered by ground-based operators (ATCO), which aims at preventing conflicts between aircrafts, by managing the resulting complexity. It mainly consists of organizing the traffic flow, and providing information and support for pilots. In order to prevent collisions, ATCOs employ traffic separation rules, which constantly ensure the maintaining of a minimum amount of empty space around airplanes. The concept of complexity in the ATC domain has received considerable attention along the years, and a large amount of studies classify complexity at several levels of analysis: environmental, organizational, traffic, and display (e.g. Cummings and Tsonis, 2005; Mogford et al., 1995). These elements influence controllers' cognitive complexity, i.e. the perceived complexity at the individual level. Many studies have been carried out for identifying factors that affect cognitive complexity in air traffic scenarios (Hillburn, 2004; Histon et al., 2002), and to devise evaluation frameworks to be applied both in simulation and real work contexts (Majumdar and Ochieng, 2007; Pawlak et al., 1996). Other studies have focused on the effects of complexity on ATCO, showing that it affects mental workload, the allocation of mental resources for accomplishing task demand in a safe and efficient manner (Athènes et al., 2002; Li et al., 2010).

According to Leplat (1978) mental workload (also referred to as cognitive workload) is a multidimensional construct, rather than a unidimensional one. In this sense the multidimensional assessment of mental workload by triangulation from physiology, performance, and subjective assessments is a fruitful approach (Parasuraman et al., 2008; Wierwille and Eggemeier, 1993). In ATC, high performance standards are usually maintained, independently of task complexity. Therefore, the monitoring of controller's performance cannot always convey the real cognitive demand imposed by the task. For this reason the need of online measurement of mental workload is an opportunity to seek. When dealing with safety-critical work contexts, the best option for workload assessment relies on unobtrusive techniques (Langan-Fox et al., 2009) and psychophysiology seems to be one of the most promising fields for

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the online measurement of the operator's state (Wilson and Russell, 2003). The main advantage of psychophysiological responses is that they do not require an overt response by the operator, and can be collected continuously with relatively low obtrusiveness. In this framework, workload has been also investigated by means of real time research techniques such as electroencephalography (Weiland et al., 2013), and optical brain imaging (Ayaz et al., 2010), but the level of intrusiveness of such techniques still represents a limitation. In contrast, the increased sophistication and accessibility of eye tracking technologies have generated a great deal of interest around eye measures (Ahlstrom and Friedman-Berg, 2006). While in the past they required invasive equipment, unsuitable for most applied settings, nowadays large advances in technology have made the equipment much more portable and capable.

In the framework of conflict detection in ATC, we explored the effects of complexity on mental workload by means of a multidimensional assessment method based on psychophysiological (eye movements), performance (response time and accuracy), and subjective measures. With respect to previous investigations, the main contribution of this study lies on the employment of eye movements for the online assessment of workload during a simulated ATC task.

Conflict detection is one of the main activities performed by ATCOs (Kallus et al., 1999). It consists of comparing trajectories of converging aircrafts and estimating the probability of a future simultaneous violation of vertical and lateral separation standards, which are commonly set to 1000 ft (feet) and 5 nm (nautical miles, the unit of distance used in aviation, which correspond to 1852 m), respectively (Loft et al., 2009). Conflict detection is carried out on radar displays and involves several subtasks such as information location, change detection, and short- and long-term predictions in a complex and dynamic environment (Li et al., 2010). To the best of our knowledge, studies in ATC domain employing psychophysiological data for workload assessment are quite limited and those dealing with conflict detection by means of ocular behaviour recording are even sparser (for a review see Langan-Fox et al., 2009). Eye tracking has been used to explore attention allocation in control tasks (Martin et al., 2011; Lokhande and Reynolds, 2012), task discrimination (Imants and de Greef, 2011), system usability (Jacob and Karn, 2003), and it has been employed as head-free input device (Alonso et al., 2013).

According to the literature dealing with conflict detection, convergence angle (CA) and minimum distance at closest approach (MD) are key factors in determining cognitive complexity. CA is a geometry factor that influences visual information acquisition, the basic cognitive process that enables successive high-level cognitive elaboration and decision making. CA directly influences distance between converging aircrafts. While wider angles increase the separation between aircraft, smaller ones reduce it. For example, two aircrafts flying with the same speed that converge with CA = 135° will keep lateral separation for a longer period with respect to aircrafts converging with CA = 60°. As a result, the eyes must perform wider saccadic movements to transit from one aircraft to the other with wider CA. In this respect, Marchitto et al. (2012) showed that an increase of CA affects both conflict detection times and ocular movements, reducing the peak velocity of large reaching saccades. According to Remington et al. (2000), trajectory comparison is faster and more accurate for smaller angles, which are usually associated to higher probability of intervention by ATCO (Loft et al., 2009).

MD is a traffic complexity factor that affects the cognitive simulation process, which involves the projection of future aircrafts positions, the estimation of the distance between them, and the comparison of such distance to the separation standards (i.e. vertical and lateral). Controllers can apply different perceptual and cognitive methods (i.e. time- or space-based strategies) for estimating future relative positions of aircrafts on the basis of relevant flight information such as speed, distance to convergence point, heading, and movement observation (Xu and Rantanen, 2003). In conflict detection, MD has been shown to predict response time, probability of intervention (Loft et al., 2009; Stankovic et al., 2008), and subjective ratings of difficulty and complexity (Boag et al., 2006).

This paper is organized as follows: information about participants, stimuli, apparatus, and a detailed description of the dependent variables with relative hypotheses is provided in Section 2. Results are presented and discussed in Section 3 with a correlational analysis followed by a factorial ANCOVA with CA and MD as predictors, and response time as covariate. Finally, conclusions are drawn in Section 4, together with practical applications and some perspectives for future work.

2. Materials and methods

2.1. Participants

Twenty-six students (22 women, mean age = 22 years, SD = 2 years) from the University of Granada—Faculty of Psychology, volunteered for course credits after signing an informed consent. They all had normal or corrected-to-normal vision (contact lenses were accepted, but not glasses). None of them had previous ATC experience. An internal committee board approved the study, which was performed in keeping with the Declaration of Helsinki.

2.2. Stimuli and apparatus

The ATC-lab$^{\text{Advanced}}$ software (Fothergill et al., 2009) was employed for building the air traffic scenarios, which consisted of a central point, i.e. convergence point, and two aircrafts with related flight information moving on predefined routes, as represented in Fig. 1. Four different types of routes were employed, i.e. vertical, horizontal, and two oblique. Aircrafts' position was updated every 5 s. Around the convergence point, a circle with a radius equal to the lateral separation standard for conflict definition (5 nm) was always presented. In this experiment the conflict detection task dealt with leveled aircrafts flying at the same altitude, thus only lateral problems were considered (Loft et al., 2009). Stimuli were

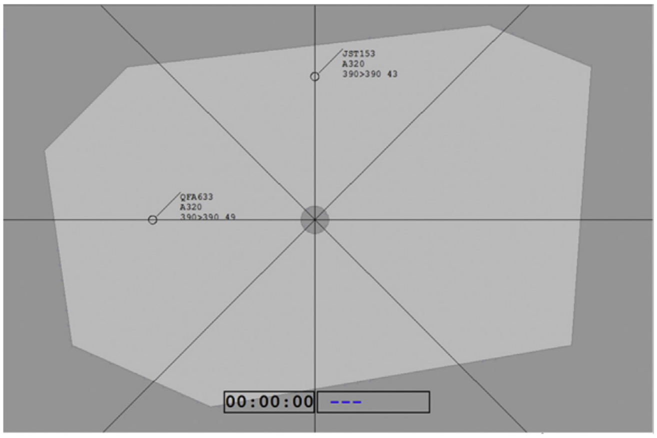

Fig. 1. Airspace structure representation. The circle around the central convergence point has a radius of 5 nm, and it subtends 1° of visual angle from a viewing distance of approximately 60 cm. Aircrafts are represented by a small circle, with relative tag containing flight data: call sign on the first line; type of aircraft on the second line; current altitude, assigned altitude, and speed on the third line.