Behavioural Brain Research 294 (2015) 246–253

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

The neuroergonomic evaluation of human machine interface design in air traffic control using behavioral and EEG/ERP measures

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HIGHLIGHTS

- We propose a neuroergonomic approach to evaluate notification designs.
- Participants performed an Air Traffic Control task with two different visual designs.
- The more salient visual design globally enhanced the performance to the task.
- Cerebral response to auditory alarms was enhanced thanks to the salient design.
- Results have implications in the evaluation of human machine interface design

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 15 July 2015
Accepted 16 July 2015
Available online 19 July 2015

Keywords:
Air Traffic Control
Attentional resources
ERP
Human machine interface evaluation
Neuroergonomics

ABSTRACT

The Air Traffic Control (ATC) environment is complex and safety-critical. Whilst exchanging information with pilots, controllers must also be alert to visual notifications displayed on the radar screen (e.g., warning which indicates a loss of minimum separation between aircraft). Under the assumption that attentional resources are shared between vision and hearing, the visual interface design may also impact the ability to process these auditory stimuli. Using a simulated ATC task, we compared the behavioral and neural responses to two different visual notification designs—the operational alarm that involves blinking colored "ALRT" displayed around the label of the notified plane ("Color-Blink"), and the more salient alarm involving the same blinking text plus four moving yellow chevrons ("Box-Animation"). Participants performed a concurrent auditory task with the requirement to react to rare pitch tones. P300 from the occurrence of the tones was taken as an indicator of remaining attentional resources. Participants who were presented with the more salient visual design showed better accuracy than the group with the suboptimal operational design. On a physiological level, auditory P300 amplitude in the former group was greater than that observed in the latter group. One potential explanation is that the enhanced visual design freed up attentional resources which, in turn, improved the cerebral processing of the auditory stimuli. These results suggest that P300 amplitude can be used as a valid estimation of the efficiency of interface designs, and of cognitive load more generally.

1. Introduction

Within safety-critical, continuously-evolving, and visually-rich environments such as air traffic control, supervisory control of emergency response, and security surveillance, operators must deal with dynamic and cognitively demanding tasks whilst confronted with temporal pressure, stress, and high-risk decision-making situations. In the case of Air Traffic Control (ATC), the main task is to guide aircraft through controlled airspace with the safety requirements of maintaining a minimal distance and an altitude of separation between them while optimizing their trajectories. Each controller is responsible for an airspace volume that is represented on a radar visualization system where numerous aircraft positions are displayed. They also must be vigilant and responsive to the occurrence of various on-screen visual notifications triggered by safety nets. In the present study, within a simulated-ATC task, we used one key safety-critical visual notification that serves to indicate an impending loss of separation between aircraft.

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http://dx.doi.org/10.1016/j.bbr.2015.07.041
0166-4328/

The auditory channel is also essential for ATC as controllers also need to exchange information with pilots and other controllers through radio and phone communications. Auditory warnings such as ground collision avoidance alerts or area infringement warnings have been increasingly integrated into ATC workstations. This recent introduction of auditory alerts raises new human factors issues, as several theories have indicated that a high cognitive load context can lead to a neglect of auditory alerts. One could argue that the high perceptual and cognitive load typical of ATC operations may consume a large proportion of attentional resources – especially when sub-optimal visual designs are used – which in turn can reduce the available attentional capacity for processing the task at hand, as well as for additional unexpected events. Indeed, according to perceptual load theory [1–3], tasks involving high perceptual load can consume most of attentional capacity, leaving little remaining for processing information that is not directly related to the focal task, such as unexpected alarms [4–7]. In this sense, several researches have shown that attentional resources are shared between vision and hearing [8–11]. Some authors also postulate that tasks with high cognitive load (e.g., load in working memory) can lead to a reduced openness to additional stimuli such as auditory distractors [12–14]. In line with these theories, we suggest that introducing efficient and salient visual designs that can reduce the perceptual and cognitive load is important not only to improve performance of the ATC task itself, but to also help preserve attentional resources that may potentially be required by other information channels.

Several studies have demonstrated that salient stimuli promote fast and effortless processing of information (see [15] for review). This automatic and preattentive process has been explained by salience map models; two-dimensional maps that encode locations to be processed in priority according to their salience. This is supported by recent work concerning the brain structures that might contain such salience maps [16]. Nardo et al. [17] showed the efficacy of a bottom-up signal for the orienting of spatial attention in a complex and dynamic environment. By using a more salient visual design for the critical visual notifications occurring in ATC, the allocation of visual spatial attention should be directed foremost toward those stimuli, sparing controllers a costly visual search in terms of attentional resources.

Concerning the evaluation of cognitive load, the use of the oddball paradigm together with event-related brain potentials (ERP) has been proposed as a valid cognitive load index in various realistic tasks such as simulated flight missions [18,19], gauge monitoring [20] or video games [21]. However, to the best of our knowledge, very few authors have explicitly used such paradigms to measure the cognitive load elicited by various human machine interface (HMI) designs. P300, usually measured between 300 and 500 ms post-stimulus [22] is one of the most commonly studied ERPs and is known to be observed during oddball paradigms. In this paradigm, participants are instructed to detect targets among non-targets (series of standard to-be-ignored stimuli; see [22]). The oddball paradigm is a well-known example that incorporates cognitive and attentional processes for stimulus recognition and attention allocation [23]. When attentional focus deviates from the target detection task (e.g., in a dual task paradigm), the P300 amplitude decreases significantly [12,24,25]. P300 is also modulated by the load of the concurrent task as increases in memory load reduce P300 component size because task processing demands increase [26,27]. Importantly, it is generally accepted that a distinction can be made between two subcomponents of the P300, the P3a and the P3b. The P3a seems to be more specifically related to the novelty of deviant auditory stimuli [28], independently of task-relevance. It has a shorter latency, a fronto-central scalp distribution and its generation involves the frontal lobe and the hippocampus. The P3a amplitude decreases with repetition and habituates rapidly. It is sensitive to variations in top-down monitoring by frontal attention mechanisms engaged to evaluate incoming stimuli and is related to the orienting response [22]. In contrast, the P3b potential, partially generated in the medial temporal lobe, has a more posterior-parietal scalp distribution, a somewhat longer latency and is less sensitive to habituation, than P3a. Several studies also suggests that the locus coeruleus-norepinephrine (LC-NE) system underlies P3b generation for a target detection task [29], which is consonant with attentional resource allocation and arousal-related effects in humans. The P3b has been thought to reflect such processes as memory access, memory storage and response initiation that are evoked by the evaluation of stimuli in tasks that require some form of action like a covert or overt response. In summary, P3a is produced in response to the processing of sensory stimuli with frontal lobe activation from attention-driven working memory changes; conversely, P3b is produced as a result of temporal/parietal lobe activation from memory and context updating operations and subsequent memory storage. In this paper, the term P300 will be used to refer to P3b, as our oddball task was task-relevant and required an open response. The high cognitive load involved in ATC should solicit the temporal lobe for sensory processing and memory operations, therefore affecting those functions and limiting auditory target processing.

Our study is based on a neuroergonomic approach [30–33] which merges knowledge and methods from cognitive psychology, system engineering, and neurosciences. This approach aims to improve the system safety and efficiency at the workplace by considering human brain functioning. We used an ATC-like synthetic environment called Laby [34] which simulates key features of a dynamic visual monitoring radar task. Participants had to acknowledge notifications displayed close to aircraft located in peripheral vision, which simulated a collision avoidance alarm. Two notification designs have previously been shown to elicit a difference in performance in this environment [34]. Box-Animation (BA), a very salient visual notification, with brackets pulsing around the notified aircraft, is extremely well detected by the controllers. On the contrary, the Color-Blink (CB) notification – similar to the classical operational design of the critical notification indicating a loss of minimum separation between aircraft – is a much less salient design that causes a lower detection rate. The Box-Animation design is very noticeable and does not require a sustained visual search to be perceived; on the other hand, the Color-Blink notifications can sometimes go unnoticed if the controller is not actively monitoring the radar screen.

2. Objectives and hypotheses

Two groups of participants were recruited. One group performed the ATC task with Box-Animation and the other with Color-Blink notifications. To further improve the level of realism, each participant performed the task according to two levels of cognitive load (tempo, i.e., the number of events per unit of time) with various numbers of aircraft in the visual scene (between 5 and 21). Simultaneously with the ATC task, participants were asked to respond to the occurrence of low probability tones and to ignore high probability tones. P300 auditory-evoked potentials were recorded from the occurrence of the tones both in parallel with the ATC task and in two control conditions (tones alone without the ATC task), as an indicator of remaining attentional resources. Measuring P300 amplitude variations will indicate if the variations in HMI design affected attentional processes and response initiation.

We predicted that the introduction of the ATC task would reduce ERPs amplitude to the rare target tones in comparison