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Pupil diameter as a measure of cognitive load during auditory-visual interference in a simple piloting task

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Abstract

Pilots face the problem of attentional selectivity, when one needs to stay focused on the current task while being attentive to other inputs, whether or not they are task-relevant. In this study we evaluate the influence of cognitive load on attentional resources available to process auditory distractors, while performing a visual task. Such cross-modal auditory-visual interference is of a particular interest in the aeronautics, as focal-task is often visual (flight deck instruments, outside) while background auditory inputs are numerous (alarms, radio, cabin-crew communications etc.). In this paper we adapted an auditory-visual interference paradigm to a simple visual piloting task. Sixteen volunteers performed both low and high load conditions while their left pupil size was continuously recorded. As shown by statistical analyses, the tonic pupil diameter was higher for high load condition accompanied with performance degradation. Therefore, the pupil diameter successfully tracked the memory load level, measured objectively with targeting accuracy and subjectively with NASA-TLX questionnaire. As also revealed by statistical analyses, the pupillary reaction reflected the processing load of irrelevant auditory stimuli. In particular, as for low load condition, the incongruent auditory stimuli evoked larger pupillary response compared to the congruent distractor, showing higher effort for resolving the conflict of auditory-visual interference. No such interference effects were found under high load condition. As indicated by tonic pupil diameter and task-evoked response, for high load condition participants run out of cognitive resources to process auditory distractors. These results are in line with the hypothesis that vision and hearing share a common pool of resources, and that attentional capture of irrelevant stimuli is impaired under increased load on working memory.

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1. Introduction

The capacity to shift attention to secondary stimuli, whether or not they are task-relevant, is often critical for adaptive behavior. In complex environments such as flight desk or air-traffic control, operators often experience the bottleneck of attentional selectivity. Despite the top-down attentional focus on a primary task, competing irrelevant stimuli (auditory or visual) can capture operator’s attention. As stated by Watkins and her colleagues [3], “Although distracting subjects from their current task, such attentional capture may have a survival advantage”. However, this ability to detect and to process concurrent stimuli might be altered during effortful thinking. This “survival advantage” is especially true in aeronautics [4-6]. Pilots or air-traffic controllers might experience a phenomenon called “inattentional deafness” [5, 19] and miss critical auditory alarms, when the focus task requires an important cognitive effort.

Though open to question [8], many researches share the unified view of attention [9, 10] that suggests the existence of a central pool of resources and not numerous independent, modality-specific ones. The interesting part about the shared attentional capacity, notably across visual and auditory modalities, is how one loaded modality can impair the sensitivity to another input. Lavie [10] conducted a review of behavioural and neuroimaging studies and concluded that high visual perceptual load leads to reduced sensitivity in hearing. She also suggested that high working-memory load can increase distractor processing. However, the latter statement was based on visual distractors and thus cannot be generalized to all modalities. Recently, Sörqvist and colleagues [7] showed that the brain response to an irrelevant sound decreased as a function of central working memory load, induced by a visual-verbal version of the n-back task. This study confirms the hypothesis of a pool of resources shared across different modalities.

In this study we evaluate the influence of memory load on available attentional resources using an auditory-visual interference paradigm during a simple visual piloting task. Such paradigm is of particular interest in the aeronautics since the primary task is often visual (displays, flight deck instruments) while secondary inputs are auditory (alarms, verbal communications). We used pupillometry as this technique is the least invasive of existing measurements of neuro- and psycho-physiological responses and can be potentially used in aeronautics to track the amount of operator’s available resources. We examined the three following questions: a) How do memory load and incongruence affect the piloting performance? b) Is the processing of irrelevant stimuli is different under different load conditions? c) How do these two factors influence brain activity, observed through the tonic pupil diameter and the amplitude of the task-evoked pupillary response?

2. Materials and methods

2.1. Participants

Sixteen healthy male right-handed volunteers (mean age 24.7±1.8), all native French speakers, participated in the study after they gave their informed written consent. All reported normal auditory acuity and normal or corrected-to-normal vision.

2.2. Experimental design

Participants performed a simple piloting task with an auditory-visual interference paradigm. They had to continuously control an aircraft with a joystick to follow one of three colored target aircraft which was indicated by a written-word instruction (Fig. 1). The cue with the target color was displayed for 1000 ms in the center of the screen in black ink every 4500 ms. Simultaneously an auditory distractor (irrelevant spoken-word color of 280 ms length), either frequent (70%) or rare, was played. Rare distractors were congruent (10%, when spoken-word coincided with the written one), incongruent (10%, when spoken-word corresponded to a color of a non-target aircraft) or neutral (10%, when no aircraft of spoken-word color was presented on the screen). For example, on Figure 1, the target color is blue; if the played word were red, it would be an incongruent distractor; if it were blue, it would be congruent; and if it were green, it would be neutral. The standard distractor was grey throughout the whole experiment. The task difficulty was induced by working memory load. Two levels of difficulty corresponded to the
delay between the displayed instruction and its execution. In low load condition, participants were asked to apply the instruction immediately; while in high load condition, they were asked to apply the instruction presented two trials previously.

Fig. 1. Time course of a task trial.

2.3. Procedure

After a short training for the two difficulty levels using 10 trials for each, participants performed two blocks of Low and High conditions counterbalanced across participants. Each block contained 250 trials. The colors of the aircraft were randomly chosen for each block between four possible colors: blue, red, yellow and green. The absent color was used for the neutral distractor. Three present colors were randomly attributed for the three displayed aircraft. The instructions were generated so as the participant had to change the target aircraft every trial.

Participants were seated comfortably in an armchair at a distance of approximately 70 cm from the 22” monitor (1680x1250) where the visual stimuli were presented. Auditory stimuli were presented via two stereo speakers, positioned at each side of the computer monitor. During the experiment, participants’ left pupil diameter was recorded with a remote SMI RED eye-tracker (SensoMotoric Instruments GmbH, Germany) at a sampling rate of 500 Hz. This device allows tracking the pupil diameter with precision despite small head movements. Before each condition, participants performed a 5-points calibration procedure of the eye-tracker. The stimuli presentation routine was implemented in C# programming language. The data acquisition routine used iViewX SDK to communicate with the eye-tracker. The data analyses were performed using custom Matlab (Mathworks) scripts. The statistical analyses were performed using Statistica (StatSoft) software.

2.4. Pupillography

The continuous pupillary recordings were cleaned from blink artifacts using linear interpolation. The data was then filtered with a “two pass” 9-point filter (low-pass) and segregated into trials according conditions. A trial was validated for the statistical analyses if the time spent to blink for the first 3 seconds of the trial did not exceed 50%. We further removed trials that exceeded point-by-point mean plus-minus 2.5 standard deviations in at least 5% of sampling points. The described procedure resulted on average in 87±16% of validated trials per condition. As a baseline value for statistical analyses we used a mean value of 2 seconds pre-stimulus.
2.5. Statistical analyses

One-way repeated measures ANOVA with within subject factor load (low vs. high) was carried out on the tonic diameter computed as a mean value for each block. To investigate the effect of the interference, a two-way repeated measures ANOVA with within subject factors load (low vs. high) and congruence (congruent vs. incongruent) was carried out on the mean value of 1 second recording starting from 1 second post-stimulus. This interval largely includes the peak of pupillary reaction known to appear about 1200-1500 ms post-stimulus [11]. Tukey’s HSD was used for post-hoc comparisons. Alpha was set to .05 in all statistical analyses.

For performance measurement, we computed accuracy for each condition as a percentage of correct aircraft targeting. We considered that an aircraft was followed correctly if the distance between the user’s aircraft and the target one was inferior to 100 pixels and it remained below this threshold for the 90% of the remaining trial length. We also performed a one-way repeated measures ANOVA with within subject factor load (low vs. high) to compare subjective NASA-TLX index for Mental Demand. For this analysis we had the data for only 13 out of 16 subjects.

3. Results

3.1. Behavioral results

The ANOVA revealed a significant main effect of task difficulty on accuracy (Fig. 2), $F(1, 15) = 9.91$, $p < .01$, $\eta^2 = 0.40$. The performance was degraded for high load condition (80±3%) compared to the low load condition (91±1%). No congruency effect, $F(1, 15) = 1.23$, $p = .31$, neither interaction, $F(1, 15) = 0.99$, $p = .41$, were found.

![Fig. 2. Mean accuracy for low and high load conditions. Error bars indicate S.E.M.](image)

3.2. NASA-TLX questionnaire

The ANOVA on NASA-TLX index for Mental Demand showed a significant difference between the low and the high load conditions (Fig. 3), $F(1,12) = 40.53$, $p < .001$, $\eta^2 = 0.77$. Participants estimated the high load condition as more mentally demanding (73.5±4.2) compared with the low load condition (34.6±6.2).
3.3. Tonic pupil diameter

The ANOVA showed a significant effect of task difficulty on tonic pupil diameter (Fig. 4), $F(1, 15) = 5.35$, $p < .05$, $\eta^2 = 0.26$. The high load condition elicited larger tonic diameter (3.77±0.14 mm) compared to the low load condition (3.68±0.14 mm).

3.4. Congruency and load interference

The 2x2 ANOVA showed a significant interaction of task difficulty and congruency factors (Fig. 5), $F(1,15) = 7.63$, $p < .05$, $\eta^2 = 0.34$. Follow-up post-hoc test revealed that the incongruent condition under low load elicited larger pupil dilation (0.10±0.02 mm) compared to the congruent condition (0.07±0.02 mm, $p < .05$) and to both incongruent (0.06±0.01 mm) and congruent (0.07±0.02 mm) conditions under high load ($p < .01$).
4. Discussion and Conclusion

In this study we manipulated working memory load while participants were performing a primary visuo-motor task. At the same time we investigated how concurrent auditory task-irrelevant stimuli affected the processing load of visual instructions as indicated by task-evoked pupillary response. The pupil diameter is a well-documented psycho-physiological proxy of effort, load on memory and arousal [11, 16-18]. As indicated by tonic pupil diameter (see Fig. 4), the high load condition required more effort compared to the low load condition. The extra effort required to complete the task under high load condition was consistent with subjective rating as indicated by the NASA-TLX score (see Fig. 3). Higher memory load made the task difficult to perform; in particular, to correctly encode, to maintain and to update two instructions in the working memory. Thus, participants showed poor performance for high load condition (see Fig. 2).

Our pupillometric findings also demonstrated that incongruent auditory distractors elicited larger phasic pupil response solely under low load condition (see Fig. 5), suggesting that an important load on memory impairs the attentional capture of irrelevant auditory stimuli. However, it did not result in a significant behavioral interference. This might be explained by sufficient available cognitive resources to inhibit the incongruent response in low load condition. These results are in line with recent findings by Sööqvist et al. [7] and also contribute to the debate [8] of whether the capacity of attention is limited centrally or independently for each modality. The focus of participants’ attention in the visual piloting task, where visual attention is critical for good performance, implied a decrease in available resources to process the auditory input with decreasing working memory. This impairment was reflected by insignificant interference under high load condition as reflected by relative pupillary dilation.

Taken together, these findings are in line with the adaptive gain theory [2] and the role of the locus coeruleus-norepinephrine (LC-NE) system in the task-evoked pupillary response [1]. Higher tonic pupil diameter under high load condition is associated with tonic mode of LC-NE system, when the current task demands a considerable effort and elicits an important excitation. Irrelevant stimuli, under such tonic mode of LC-NE discharge frequency, do not evoke a sufficient reaction to capture the attention. This mode of LC activation is associated with disengagement from the current task (and exploration of alternatives). Low load condition, in turn, demands less cognitive effort, and the LC discharge frequency corresponds to its phasic mode: a moderate tonic pupil diameter and sufficient attentional resources to process the stimuli, even the irrelevant ones. This mode of LC activation is thought to facilitate the exploitation of the current task and to help to optimize task performance. Note, however, that 1) there is a continuum of states between phasic and tonic LC-NE activities; and, thus, no single state can be described as purely phasic or tonic mode; and 2) in the context of the present study, one cannot speak of disengagement for high load condition since the accuracy score was still considerable (80%) and no alternative tasks were proposed for
exploration. Nevertheless, the confrontation of our results with the adaptive gain theory seems relevant, since 1) there is a link between activities in the LC-NE system and the ventral attention network and [2, 12-14]; and 2) ventral attention network is known to be involved in reorienting of attention to salient auditory stimuli even independent of the current behavioral context [3, 15].

In conclusion, our findings suggest that the pupil diameter can be an efficient tool to measure cognitive load in ecological settings. In the present study we adapted the auditory-visual interference to a simplified piloting task. In this context, cognitive load tracked by pupil diameter included, in particular, load on memory induced by different task difficulties, and effort of processing irrelevant auditory stimuli. As revealed by pupillometry, participants run out of attentional resources to process auditory distractors in the high load condition. These results are in line with the hypothesis that vision and hearing share a common pool of resources, and that attentional capture of irrelevant stimuli is impaired under increased load on working memory.

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