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The impact of luminance on tonic and phasic pupillary responses to sustained cognitive load

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ABSTRACT

Pupillary reactions independent of light conditions have been linked to cognition for a long time. However, the light conditions can impact the cognitive pupillary reaction. Previous studies underlined the impact of luminance on pupillary reaction, but it is still unclear how luminance modulates the sustained and transient components of pupillary reaction – tonic pupil diameter and phasic pupil response. In the present study, we investigated the impact of the luminance on these two components under sustained cognitive load. Fourteen participants performed a novel working memory task combining mathematical computations with a classic n-back task. We studied both tonic pupil diameter and phasic pupil response under low (1-back) and high (2-back) working memory load and two luminance levels (gray and white). We found that the impact of working memory load on the tonic pupil diameter was modulated by the level of luminance, the increase in tonic pupil diameter with the load being larger under lower luminance. In contrast, the smaller phasic pupil response found under high load remained unaffected by luminance. These results showed that luminance impacts the cognitive pupillary reaction – tonic pupil diameter (phasic pupil response) being modulated under sustained (respectively, transient) cognitive load. These findings also support the relationship between the locus-coeruleus system, presumably functioning in two firing modes – tonic and phasic – and the pupil diameter. We suggest that the tonic pupil diameter tracks the tonic activity of the locus-coeruleus while phasic pupil response reflects its phasic activity. Besides, the designed novel cognitive paradigm allows the simultaneous manipulation of sustained and transient components of the cognitive load and is useful for dissociating the effects on the tonic pupil diameter and phasic pupil response.

1. Introduction

Pupillary reactions independent of luminance have been linked to cognition since the early sixties (e.g. Hess and Polt, 1964; Kahneman and Beatty, 1966). The pupillary reaction can be divided into two components: tonic pupil diameter and phasic pupil response (Beatty, 1982b). Tonic pupil diameter reflects a sustained component of the pupillary response and is expressed as an absolute pupil diameter. Often, tonic pupil diameter is also used as basal pupillary diameter. In turn, phasic pupil response refers to a transient component of the pupillary response and is expressed as dilation relative to some basal pupil diameter. While the typical order of magnitude of the tonic pupil diameter is 1 mm, that of phasic pupil response is 0.1 mm. Many authors stated that the magnitude of phasic pupil response to a given task was independent of tonic pupil diameter (Beatty, 1982a, p.284; Bradshaw, 1969; Kahneman and Beatty, 1967). Thus, given the presumption of the independence of these two pupillary components, Beatty (1982a) concluded that it is possible to compare the phasic pupil responses issued from various set-ups and reported by different laboratories. Notably, in the review, he presented a table of quantitative comparison of qualitatively different cognitive tasks (memory, language, reasoning and perception). The table confronted the results obtained by different researchers and permitted to see that, for example, the storage in memory of four words makes the pupil dilate more than that of a multiplicand, which is roughly equivalent to retaining in memory two digits. According to the corresponding pupillary reactions, it also put an easy multiplication problem higher (phasic pupil response about 0.1 mm larger) than a hard auditory discrimination task. However, one may call in question such ordering assuming that multiplication of two digits is sometimes easier than detection of a deviant sound. Such task classification, using the magnitude of phasic pupil response as a marker of difficulty, would prevail but on one condition; if tonic pupil diameter does not impact phasic pupil response. Suppose, indeed, that tonic pupil diameter varies as a function of the experimental setup at one hand, and phasic pupil response depends on tonic pupil diameter at another. In this case, in order to compare results issued from different experimental setups one should first make sure that the conditions were the same or at least similar. The investigation of these questions is of an

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importance when using pupil reaction as a marker of stress or workload in ecological conditions where such factors as light are difficult to control. Because if there exists a strong relationship between tonic pupil diameter and phasic pupil response, the transportability of laboratory results into real life conditions for applications such as human factors in aviation needs a whole reflection apart.

The dependence of the extent of a physiological reaction to an event on the pre-stimulation basal level was named "law of initial value" in the fifties (Lacey, 1956; Wilder, 1967). Lacey (1956) postulated that a high autonomic excitation before a stimulus would affect the reactivity and diminish the response but did not refer to the pupil, talking rather about skin resistance, heart rate, blood pressure, muscle potentials, etc. Recently, a few mentions of this law appeared in pupillometric studies (Gilzenrat et al., 2010; Höfle et al., 2008; Van Gerven et al., 2004). Formulated in terms of tonic and phasic components of pupillary response, the law of initial value would postulate that a large tonic pupil diameter would imply a smaller phasic pupil response. On the other hand, Sokolov in his work on orienting response (1963) also distinguished tonic and phasic components. In particular, his model (including pupil dilation response) incorporated a response amplifier associated with general arousal (tonic state) which amplifies the phasic response. Thus, according to Sokolovian work, large tonic pupil diameter would imply a larger phasic pupil response. Afterwords, Jin (1992) reviewed experimental data and proposed that the law of initial value should be revisited as follows: "The higher the initial value, the greater the organism's following reactivity, although a tendency to reversed responses may occur when the initial value reaches its upper extremity." Therefore, Jin proposed to consider the law of initial value as a restriction of pupillary dynamic range, i.e. when the pupil is already large, it cannot dilate further. Thus, the direction of the law is still questionable.

The tonic pupil diameter has numerous sources of variation (Tryon, 1975). For instance, it is modulated by general organism's arousal, sustained cognitive load, or light conditions, both ambient illumination and focal luminance. When tonic pupil diameter is modulated by vigilance state, an inverse relationship between tonic and phasic pupil diameters was found by Gilzenrat et al. (2010) in an auditory oddball task. The authors discussed this finding with regard to the law of initial value but considered it as exclusively mechanical. Therefore, the authors verified if the inverse relationship between tonic pupil diameter and phasic pupil response held true when tonic pupil diameter was modulated by light conditions and proved it false in that case. This finding was afterward confirmed by Murphy et al. (2011) also in an auditory oddball task and, more recently, by de Gee et al. (2014) in a perceptual decision-making paradigm and Knapen et al. (2016) in an auditory vigilance task. Steiner and Barry (2011), on the other hand, in their study on orienting reflex, found that vigilance state modulated tonic pupil diameter but not phasic pupil response. As for cognitive tasks implying working memory, Steinhauer et al. (2004) found that the phasic pupil diameter was modulated by ambient illuminance when engaged in sustained processing. More recently, Peysakhovich et al. (2015) found that the phasic pupil diameter was modulated by the screen luminance in a short-term memory task. Most recently, Pfleging et al. (2016) also studied pupillary response, manipulating illuminance and luminance during a cognitive task. However, the authors used a one-factor-at-a-time method that does not enable the investigation of the illuminance-luminance interaction and reported exclusively the absolute pupil diameter values making impossible to compare tonic and phasic pupil responses. Altogether, to be able to compare pupil reactions issued from different studies that maintain different light conditions, and to transport the laboratory results into real-life applications, it is important to investigate further the relationship between the tonic and phasic components of the pupillary response and the factors that modulate these components. The pupillometry literature still has not given a clear answer to these questions, and a further investigation is needed. To the best of our knowledge, no studies investigated the impact of luminance on the tonic and phasic components of the pupillary response during sustained cognitive load.

Therefore, in the present study, we manipulated the sustained cognitive load and the screen luminance. To explore both tonic and phasic pupil response and so that both components would reflect cognitive processing, we used the Toulouse N-back Task – a novel working-memory task that couples n-back task with mathematical problems solving. This paradigm has the particularity to combine sustained memory load during a block and transient stimulus processing during each trial. We did not manipulate the transient load, and the stimulus processing was equal for all conditions. The objective of the study was to investigate the impact of luminance on the tonic and phasic pupil response during various levels of sustained cognitive load. We assessed the following questions: a) How does the luminance impact both tonic and phasic pupillary components under different sustained cognitive load conditions? b) What is the relationship between tonic and phasic pupil response during sustained cognitive load?

2. Materials and methods

2.1. Subjects

The subjects were 14 healthy volunteers (4 females, 2 left-handed, age 26.6 ± 5.0, educational level 15.9 ± 2.4), students and staff of ISAE-SUPAERO (French Aerospace Engineering School). All reported normal auditory acuity and normal or corrected-to-normal vision, had no history of neurological diseases and were free of the regular use of medication. The subjects slept 7.1 ± 1.1 h the night before the experiment and 8 out of 14 took coffee at least 2 h before the start of the experiment. All participants gave their written informed consent in accordance with local ethical board requirements before the experiment.

2.2. Experimental design and procedure

The experiment was conducted in a dimly lit sound-attenuated room with one indirect light source behind the participants' back. The ambient illuminance was about 10 lx at the site of participants' eyes. Participants were seated at a viewing distance of approximately 65 cm from the 22-in. LCD monitor (1680 × 1250 pixels screen resolution) with a refresh rate of 60 Hz. Stimulus display and behavioral data acquisition were conducted using Psychophysiological Toolbox V3 for Matlab.

Participants performed the Toulouse N-back Task (Mandrick et al., 2016; Causse et al., 2017) – an N-back task coupled with mathematical calculation – where participants have to solve a simple mathematical formula to perform the n-back task on the result of arithmetic operations. Mathematical operations were either additions or subtractions, of which all summands were a multiple of 5 (e.g., 65 + 10, 50–25 etc.). Two levels of working memory load were produced with 1-back and 2-back tasks. Two levels of luminance were produced by changing the screen background from block to block that was either gray (~11 cd/m^2) or white (~28 cd/m^2). As illustrated in Fig. 1, each block began with the announcement of the working memory load ("1-BACK" or "2-BACK"; 1.76° × 7.88° in the center of a screen) for 15 s. It allowed participants to calm down between blocks but primarily served as an accommodation period to the display luminosity. Each block was comprised of 25 trials that began with the presentation of a mathematical problem (1.76° × 6.15° in the center of a display) for 3000 ms, followed by a 1000-ms blank screen. Participants had to resolve the current problem and then to match the result with the previous (1-back) or with the result of the problem two presentations earlier in the sequence (2-back). Subjects were instructed to respond as quickly and accurately as possible for each trial. They had to answer via a response Cedrus Pad placed under their right and left index fingers and containing a green "yes" key and a red "no" key. Participants were told to press "no" key