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Pupil dilation reveals top–down attentional load during spatial monitoring

Matteo Lisi[a,*], Mario Bonato[b], Marco Zorzi[c,d]

[a] *Laboratoire Psychologie de la Perception (CNRS UMR 8242), Université Paris Descartes, Paris, France*
[b] *Department of Experimental Psychology, Ghent University, Ghent, Belgium*
[c] *Department of General Psychology and Center for Cognitive Neuroscience, University of Padova, Padua, Italy*
[d] *IRCCS San Camillo Hospital, Lido Venice, Italy*

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ABSTRACT

It has long been known that the diameter of human pupil enlarges with increasing effort during the execution of a task. This has been observed not only for purely mechanical effort but also for mental effort, as for example the computation of arithmetic problems with different levels of difficulty. Here we show that pupil dilation reflects changes in visuospatial awareness induced by attentional load during multi-tasking. In the single-task condition, participants had to report the position of lateralized, briefly presented, masked visual targets (”right", "left", or "both" sides). In the multitasking conditions, participants also performed additional tasks, either visual or auditory, to increase the attentional load. Sensory stimulation was kept constant across all conditions to rule out the influence of low-level factors. Results show that event-related pupil dilation strikingly increased with task demands, mirroring a concurrent decrease in visuospatial awareness. Importantly, pupil dilation significantly differed between two dual-task conditions that required to process the same number of stimuli but yielded differed levels of accuracy (difficulty). In contrast, pupil dilation did not differ between two conditions which were equally challenging but differed both in the modality of the dual task (auditory vs. visual) and in the number of stimuli to be attended. We conclude that pupil dilation genuinely reflects the top–down allocation of supramodal attentional resources.

1. Introduction

The measurement of pupil diameter (i.e., 'pupillometry') has been used in psychology for more than 50 years as a psychophysiological index of processing load and resource allocation (Hess & Polt, 1960; Hess & Polt, 1964; Kahneman & Beatty, 1966). Increased pupil diameter (dilation/mydriasis) is associated with greater effort, and this has been observed both for purely mechanical effort (e.g. picking up different weights, see Nunnally, Knott, Duchnowski, & Parker, 1967) and for mental effort (e.g. processing arithmetic problems with different levels of difficulty, see Ahern & Beatty, 1979). The degree of pupil dilation has been shown to reflect also the difficulty of lower-level, more sensorial, tasks, such as the discrimination between tones of different pitch (Kahneman & Beatty, 1967). Accordingly, given the sensitivity of pupil diameter to processing load, Kahneman (1973) used it as the primary measure of processing load in his *effort theory of attention*, suggesting that it could provide a window on the "intensive" aspects of attention, intended as distinct from the more often studied "selective" aspects. More recently, changes in pupil size have been suggested to reflect not only attentional allocation but also a broad range of processes involved in cognitive control (Laeng, Ørbo, Holmlund, & Miozzo, 2011; Brown et al., 1999; van Steenbergen & Band, 2013).

Which mechanism links the size of the pupil to mental effort? It is worth remembering that the size of the pupil is determined primarily by the exposure to light and the accommodation reflex. Changes in illumination can elicit pupil dilation up to a maximum of more than double of its typical size (about 3 mm, MacLachlan & Howland, 2002). Changes in pupil size reflecting cognitive processes are instead much smaller (often less that 0.5 mm). These changes can be extracted by performing time-locked averaging with respect to the event of interest, and are often normalized with respect to pupil size at baseline, tipically measured before the onset of the event (Beatty & Lucero-Wagoner, 2000; Beatty, 1982). These cognitively-related pupil dilation responses

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* Corresponding author at: Laboratoire Psychologie de la Perception, Université Paris Descartes, 45 rue Des Sant-Pères, 75006 Paris, France.
E-mail addresses: matteo.lisi@parisdescartes.fr, matteo_lisi@yahoo.it (M. Lisi).

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have been recently linked to a neurotransmitter system, the locus coeruleus–noradrenergic (LC–NE) neuromodulatory system (Aston-Jones & Cohen, 2005). Specifically, it has been shown that pupil size correlates with tonic activity of locus coeruleus (LC) in several non-human species (Aston-Jones & Cohen, 2005), and that pupil size in humans correlates with behaviors that have been linked with LC–NE activity in a variety of tasks (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Jepma & Nieuwenhuis, 2011; Murphy, Robertson, Balsters, & O'Connell, 2011). Because the LC is the sole source of the neurotransmitter norepinephrine (NE) in the brain, it has been suggested that activity within the NE system is reflected in the dilation of the eye's pupil, which in turn would offer a unique window on the NE system activity (Laeng, Sirois, & Gredeback, 2012).

The LC–NE system has widespread connections and is thought to be involved in many cognitive functions, including attention and alertness (Petersen & Posner, 2012; Posner & Petersen, 1990). One recent hypothesis ascribes to the LC–NE system a central role in the functional integration of attentional networks (Corbetta, Patel, & Shulman, 2008). Another theory, the adaptive gain theory (Aston-Jones & Cohen, 2005), maintains that the LC–NE system modulates neural gain (responsivity) thorough the brain. It is thought to have two modes of activity, phasic and tonic (or more likely a continuum between these two modes), corresponding to high or low neural gain. In the phasic mode, LC cells exhibit large phasic activations, typically related to the processing of task-relevant stimuli. This mode of functioning is usually associated with higher levels of task engagement and performance (Aston-Jones, Rajkowski, & Cohen, 1999; Aston-Jones, Rajkowski, Kubiak, & Alexinsky, 1994; Gabay, Pertzov, & Henik, 2011; Murphy, Robertson, Balsters, & O'Connell, 2011; Usher, 1999). Conversely, in the tonic mode, LC cells show smaller, sporadic phasic activations, but higher tonic activity. This is associated with increased distractibility and poorer performance in tasks that require focused attention. Nevertheless, the tonic mode leads to increased sensitivity in detecting novel or unexpected stimuli, which can be advantageous in some environmental contexts. The theory thus proposes a crucial role for the LC–NE system in regulating task engagement and behavioral flexibility according to different environmental contingencies (Aston-Jones & Cohen, 2005). Importantly, the adaptive gain theory predicts larger phasic responses in LC activity when subjects engage in a demanding task, which are accompanied by larger pupil dilations (Gabay et al., 2011).

In the present study we investigated whether the amplitude of pupil dilation could reflect the level of 'pure' top–down attentional load, as opposed to experimental manipulations where attentional load increases as a function of the number of stimuli presented, or of the physical similarity of the stimuli to be discriminated (e.g., Ahern & Beatty, 1979; Beatty, 1982; Kahneman & Beatty, 1996 Kahneman & Beatty, 1967). For this purpose, we designed an experimental paradigm characterized by a dual-task manipulation during a spatial monitoring paradigm. Our approach is based on a method that was proven to induce striking contralesional deficits of visual awareness in patients with unilateral brain damage (Bonato, Priftis, Marenzi, Umiltà, & Zorzi, 2010; Bonato, 2015). Two features make this approach particularly suitable for measuring event-related pupillary responses. The first is that stimuli are kept identical across task conditions with different levels of attentional load (Bonato, 2012; also see Bonato, Spironelli, Lisi, Priftis, & Zorzi, 2015, where this feature is exploited in a ERP study). The second feature is that patients' spatial monitoring performance is characterized by similar rates of contralesional omissions across very different dual tasks (Bonato, Priftis, Umiltà, & Zorzi, 2013), suggesting the engagement of unspecific, supramodal attentional resources.

Attentional load has been shown to interfere with visuospatial orienting also in healthy subjects, although to a much lesser extent (Bonato et al., 2015; Dodds et al., 2008; O'Connell, Schneider, Hester, Mattingley, & Bellgrove, 2011; Peers, Cusack, & Duncan, 2006; Pérez et al., 2009). Following Bonato et al. (2010), in the present study we assessed the effect of attentional load on visuospatial awareness by means of a primary spatial task, common to all the conditions, which consisted in verbally reporting the position of lateralized, briefly-presented, masked targets that could appear either on the left, on the right, or on both sides. The aims of our study were twofold: first, we sought to determine whether pupil dilation provides an index of 'pure' top–down attentional load in healthy participants and, second, whether pupil dilation correlates with behavioral performance in the visuospatial monitoring task.

2. Methods

2.1. Participants

Twenty-four participants (mean age 23.3 years, range 19–29 years, 15 females) participated in the study. All participants signed a written informed consent and had normal or corrected to normal visual acuity. The study was approved by the local Ethics Committee (Department of General Psychology, University of Padova).

2.2. Apparatus

The experiment was conducted in a quiet and dimly lit room. The only sources of light were the computer screen and a lamp (tungsten incandescent light bulb, 25 W/375 lm) placed immediately behind the monitor and directed toward the wall. Participants were seated with the head positioned on a chin rest at a distance of 60 cm from the computer screen. The experiment was run on a PC, using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Eye movements were recorded with a sampling frequency of 60 Hz through a Tobii T120 screen-based eyetracker (Tobii Technology, Sweeden), which was used also to present stimuli through its embedded 17-inch TFT monitor.

2.3. Stimuli

Visual stimuli were presented on a gray background ($31.5\ \mathrm{cd/m^2}$) and consisted of lateralized targets for the primary spatial task, plus a colored shape appearing at fixation and a brief binaural sound presented through headphones for the secondary task(s). The lateralized targets (Fig. 1, panel A) consisted in black ($0.33\ \mathrm{cd/m^2}$) dots of 0.75° of diameter, appearing either on the left, on the right, or both sides of the screen (eccentricity 14°). Their duration was calibrated according to individual sensitivity (see Section 2.4). The shape presented at fixation was either a square, a rhombus or a circle (matched area), filled in by one out of three colors (orange, green, blue), resulting in 9 different color-shape combinations (see Fig. 1, panel B). The sound was a 100 ms pure tone (three frequencies equally spaced in log-units were used: high, 796 Hz, medium, 450 Hz and low pitch, 250 Hz). After the disappearance of the targets, two masks (one for each side, left and right) were presented (4 black dots, arranged as the corners of a square centered on target position; side 1.8°).

2.4. Procedure

The experiment consisted in 4 experimental blocks (81 trials each) plus a pre-test block, to be completed in one session, lasting approximately one hour. Each trial (Fig. 1, panel A) started with the presentation of a black fixation cross in the center of the screen. Gaze contingency was then implemented: targets were concurrently presented 800 ms after participants maintained gaze within