Pupil dilation reveals top–down attentional load during spatial monitoring

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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.

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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

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 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 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

A

B
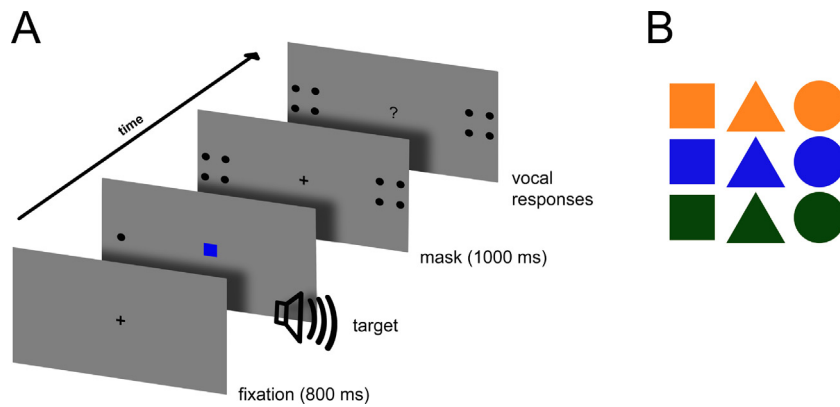
Fig. 1. (A) Schematic representation of an experimental trial (left target). (B) The possible combinations of color and shape for the central stimulus. The three shapes subtended the same area on the display. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

an area of 2° around the center of the screen for at least 200 ms consecutively. Shortly after the presentation of the targets, the lateralized mask appeared on both sides, simultaneously with the fixation cross which replaced the central shape. One second later, a question mark appeared in the middle of the screen to prompt the participant to vocally report the target stimuli according to task instructions.

While the stimuli were always identical, the instructions changed across the four experimental blocks, thereby yielding four different task conditions. Each participant performed: (i) a *single task* (*single*), where only the position of the lateralized targets had to be reported (left, right, both sides); (ii) a visual dual-task (*color*), which required to report target position and the color of the central shape (green, blue or orange); (iii) an auditory dual-task (*sound*), which required to report target position and the pitch of the binaural sound (high, medium or low pitch); and (iv) a visual triple-task (*shape-color*), which required the participant to report target position and both the color and the type of central shape (square, rhombus or circle). The experimenter coded participants' responses online through a computer keyboard. The order of the four blocks (i.e., task conditions) was counterbalanced across participants.

The duration of visual stimuli was adapted to individual sensitivity in a pre-test block (single task condition), through a brief (54 trials) weighted up-down staircase procedure (Kaernbach, 1991) with a target performance ~75% correct responses. This allowed to roughly equate the difficulty of the primary task across participants. The average duration was 161 ms (standard deviation 88 ms, range 67–317 ms).

2.5. Pupil size analysis

We analyzed the event-related pupillary response, time locked to the onset of target stimuli, for each task condition/block. Pupil size (sampled at 60 Hz together with gaze position) was then analyzed offline using R (R Development Core Team, 2008). Data from the left and right pupil were averaged together, and gaps in the recordings shorter than 100 ms (due for instance to brief eyeblinks or to eyetracker faults) were linearly interpolated. For each participant and task condition, pupil data were segmented in epochs aligned to target onset. Each epoch was then low-pass filtered with a central moving average filter of 13 samples (at a sampling frequency of 60 Hz this corresponds to a cut-off frequency of 2 Hz), and transformed to differences relative to a baseline level, namely the average pupil size in the 500 ms before target onset. Only trials with all correct responses (both to the primary task and to the additional dual tasks, when required) were included in the pupil size analysis.

3. Results

Gaze position recordings were analyzed offline to determine the presence of eye movements. Trials in which the recorded gaze position during the fixation-mask interval deviated from the fixation cross by more than 2°, and for more than 100 ms consecutively, were excluded from subsequent analysis (4% of total trials). Trials with gaps in the recordings longer than 100 ms were excluded (2% of total trials).

3.1. Behavioral results

Mean accuracies for the additional tasks (i.e., other than the primary task of reporting lateralized targets position) were 99% correct for the *color* task, 94% for the *color-shape* task and 92% for the *sound* task respectively. Using the lme4 library (Bates & Sarkar, 2007), available for the open-source software R (R Core Team, 2015), we fitted a generalized mixed-effect model (Pinheiro & Bates, 2000) with the logistic as link function and the accuracy of responses to dual-tasks as dependent variables; participant was included as random effect factor and task condition as fixed effect predictor. To test the statistical significance of each fixed effect predictor, we compared the change in the residual deviance between the full and a reduced model (i.e., without the selected predictor) using a likelihood ratio test. Results showed a significant effect of task condition [χ^2 (2) = 68.36, $p < 0.001$]. Specifically, accuracy in the *color* task was higher compared to both the *sound* task [$\beta = -2.52$, $z = -8.24$, $p < .0001$] and the *shape-color* task [$\beta = -2.21$, $z = -7.16$, $p < .0001$]. A significant difference also emerged between the *sound* and *shape-color* tasks [$\beta = 0.3$, $z = 2.22$, $p < .05$].

We then analyzed response accuracy in the primary task (spatial monitoring), excluding from the analysis those trials with wrong responses to the additional tasks (whenever required). We again applied a logistic mixed effects model, with the proportion of correct responses to the lateralized targets as dependent variable. The model included task condition (*single, color, shape-color, sound*) and lateralized target position (left, right or both) as fixed-effect predictors and participant as random-effect factor. Results showed both a significant effect of task condition [χ^2 (3) = 17.93, $p < 0.001$] and of target position [χ^2 (2) = 253.69, $p < 0.001$]. The interaction between task condition and target position was not significant [χ^2 (6) = 11.18, $p = 0.08$], although there was a trend for a greater decrease in performance with increasing load for the left target condition (see Fig. 2, panel A). The condition with targets appearing in both hemifields (bilateral) yielded a significantly lower accuracy with respect to the left target condition, as indexed by the parameter of the corresponding contrast in the model [$\beta = -1.42$, $z = -7.89$, $p < .0001$]. There was no difference between the two
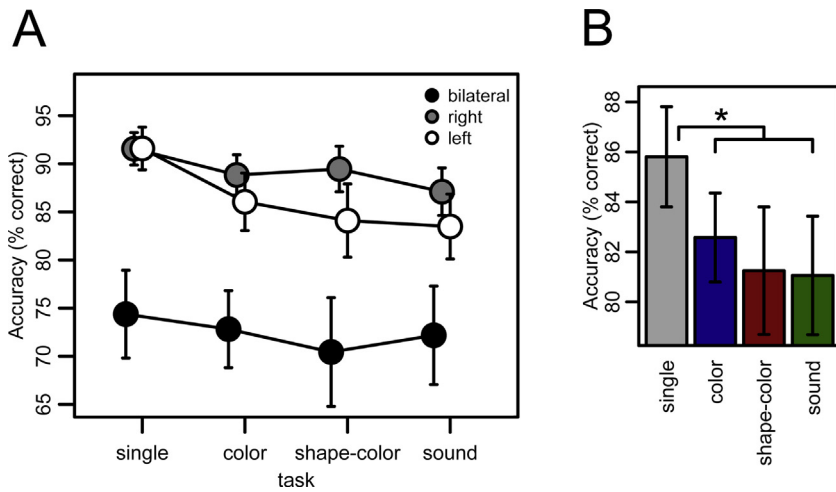
Fig. 2. Behavioral data (A) Mean accuracy in the primary task (spatial monitoring) as a function of target position. (B) Mean accuracy in each task, collapsed across the different target positions. Error bars represent SEM.

unilateral conditions (left vs. right targets) [$\beta = -0.4$, $z = -0.2$, $p = 0.83$]. It is important to remark that for the current analysis we considered as errors also omissions of a single lateral target in bilateral trials, as well as responses that indicated two targets in unilateral trials. The significant main effect of task condition indexed the decreased accuracy in reporting the lateralized targets when multitasking (see Fig. 2, panel B). Indeed all multitasking conditions yielded a significantly lower accuracy relative to the single task [*color*, $\beta = -0.66$, $z = -3.4$, $p < .001$; *color-shape*, $\beta = -0.75$, $z = -3.89$, $p < .001$; *sound*, $\beta = -0.83$, $z = -4.31$, $p < .001$]. The regression coefficients were compared again after switching the contrasts for the 'task condition' factor but no significant differences in accuracy between the three multitasking conditions emerged (all $ps > .05$). The latter finding shows that performance level in the spatial task does not reliably discriminate the different types of multitasking conditions.

3.2. Event related pupillary response

Due to the slow time-course of the changes in pupil diameter we took as a measure of pupil dilation the average dilation in the time window between 1.25 and 1.75 s after stimulus onset (a window that comprised the maximum dilation in all the four tasks), which was then analyzed as a function of task condition (see Fig. 3, panel A). A repeated-measures ANOVA confirmed a main effect of task on pupil diameter changes [$F(3, 69) = 14.22$, $p < .0001$]. Planned comparisons revealed that the *color* task elicited a significantly greater dilation than the *single* task [$t(23) = 2.46$, $p = 0.02$]. Both the *sound* and the *color-shape* tasks elicited a significantly greater dilation than the *color* task [*sound*, $t(23) = 2.55$, $p = 0.02$; *shape-color*, $t(23) = 3.30$, $p = 0.003$], but they did not differ from each other [$t(23) = 1.24$, $p = 0.23$] (all t-test comparisons were paired and two-tailed).

By comparing pupil data to the accuracy in the primary spatial task, it can be noted that the increase in pupil dilation closely mirrors, at the group level, the reduction in response accuracy (see Fig. 3, panel B). The relation between the two variables is much less evident at the individual level, as a consequence of different task orders and the well-known effect of arousal and fatigue on pupil size (McIntire, McIntire, McKinley, & Goodyear, 2014; Morad, Lemberg, Yofe, & Dagan, 2000). Since task order was counterbalanced across participants, the pattern of data can be better appreciated at the group level, where carry-over effects were equated. Indeed the average response accuracy showed a

significant negative correlation with peak pupil dilation across the 4 blocks, $r(2) = -.96$, $p = 0.04$, two-tailed. In summary, pupil dilation precisely characterized concurrent processing load during a spatial monitoring task and mirrored the behavioral performance, as indexed by the group-level correlation with the response accuracy in the spatial task. Moreover, pupil dilation also proved to be more sensitive than response accuracy, as it highlighted a significant difference between the *color* task and both the *sound* and *shape-color* tasks; this difference was present as a trend in mean accuracies, but it did not reach statistical significance.

We investigated also whether the amplitude of pupil dilation was larger for bilateral vs. unilateral target. We carried out a repeated-measures ANOVA with the amplitude of pupil dilation as dependent variable, task condition and target number (2, bilateral, vs 1, unilateral, where unilateral includes both left and right targets) as within-subjects factors. Neither the effect of target number [$F(1, 23) = 1.49$, $p = 0.23$], nor the interaction between task and target number [$F(3, 69) = 0.86$, $p = 0.46$] were significant. The same analysis performed on the average pupil diameter in the 500 ms baseline period did not reveal any significant effect (see top left inset in panel A of Fig. 3) [task, $F(3, 69) = 0.64$, $p = 0.58$; target number, $F(1, 23) = 1.34$, $p = 0.26$; interaction between task and target number, $F(3, 69) = 1.08$, $p = 0.36$].

3.3. Hemi-field bias

Incorrect responses during the spatial monitoring task were further analyzed to explore the role of increased task demands on spatial awareness. This additional analysis was intended to exclude the presence of spatially asymmetric performance, though a strong spatial bias is a-priori unlikely in the absence of brain damage. The probability of a correct response to target position (Fig. 2, panel A) was lower in the bilateral than in the unilateral target condition. To identify a potential hemifield bias we further analyzed the pattern of errors in bilateral trials. A laterality index on the incorrect bilateral trials was computed for each participant and task condition as follows:

$$\text{laterality index} = \frac{R - L}{R + L}$$

R and L indicate, respectively, the number of right and left responses given by participants in bilateral trials (i.e., errors). Though the mean index across participants was positive for three out of four conditions, thereby suggesting a rightward bias [single = 0.11; color = 0.26; sound = 0.17; color-shape = −0.03], all t-tests against
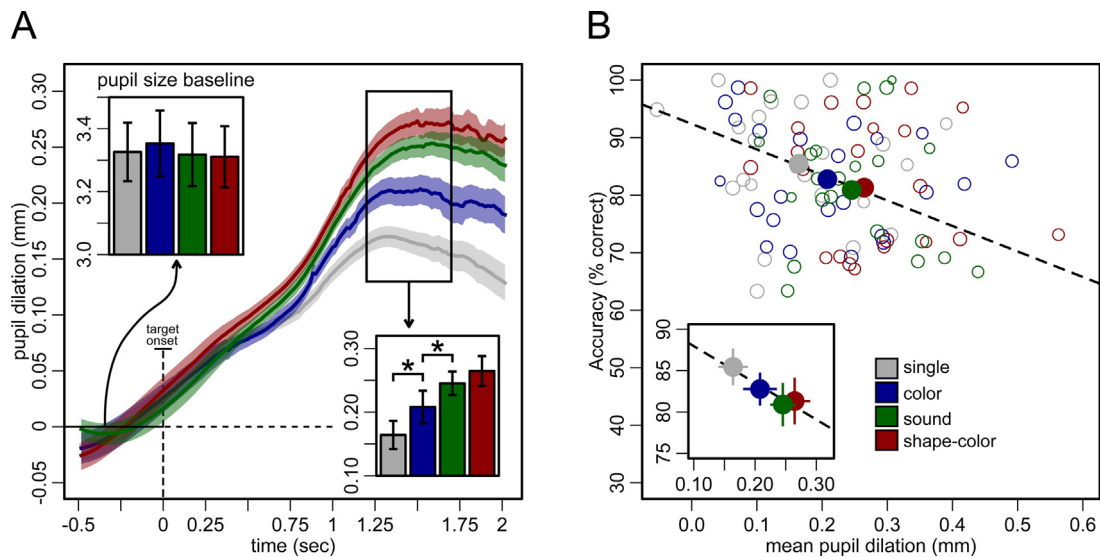
Fig. 3. Pupil dilation data. (A) Time-course of dilation patterns. The top left inset shows mean values of pupil diameter at pre-stimulus baseline (500 ms before target onset), whereas the bottom right inset shows mean pupil dilation in the 1.25–1.75 s post-stimulus time window corresponding to the black, top right rectangle superimposed on the dilation time-course. The vertical, dashed line represents target onset. (B) Relation between response accuracy to the lateralized targets and pupil dilation across the different tasks (magnified within the inset). Empty dots represent individual data, and filled dots represent group means. Error bands and bars represent SEM.

zero failed to reach significance (all $p > 0.05$). A repeated-measures ANOVA with task condition as within subject predictor also did not reveal any significant effect.

4. Discussion

We examined whether event-related pupillary responses were sensitive enough to characterize 'pure', top–down, attentional load. We manipulated attentional load across four task conditions by adding one/two concurrent tasks to the primary spatial task (detection of lateralized targets). Importantly, across all single and dual-task conditions the stimulation was kept constant: this was necessary because it is known that each and every stimulus is likely to elicit a pupil dilation response (e.g., Hess & Polt, 1960; Laeng et al., 2012; Laeng & Falkenberg, 2007; Partala & Surakka, 2003). We found that event-related pupil dilation (time locked to stimulus onset) was modulated by the increasing task demands. As expected, the single task yielded the highest accuracy as well as the smallest pupil dilation in comparison to all other task conditions. Spatial monitoring in the *color* task (which implied dual tasking) was performed with lower accuracy than when it was performed in isolation during the *single* task, and increased pupil dilation paralleled this finding. In turn, the *color* task produced a lower dilation with respect to the two other tasks (*sound* and *color-shape*), which on the contrary did not differ from each other in terms of accuracy. The pattern of results clearly indicates that our top–down manipulation of task difficulty not only resulted in increased error rate in the primary spatial task but also committed participants to greater task engagement, as indexed by the larger stimulus-related pupil dilations. Our experimental design allowed to disentangle processing load from potential confounds like the number of stimuli that had to be responded to and/or the number of alternative responses. Indeed, the 'triple-task' (*color-shape*) and the *sound* dual-task conditions elicited a similar pupillary response and also yielded a similar error rate, even though the number of stimuli to be discriminated was greater in the 'triple' task. This finding allows to rule out the mere number of items in working memory (Beatty & Lucero-Wagoner, 2000; Kahneman & Beatty, 1966; Kahneman, Peavler, & Onuska, 1968; Granholm, Asarnow, Sarkin, & Dykes, 1996) or other response selection/preparation

mechanisms as the main determinants of pupil dilation differences. In contrast, it suggests that the two task conditions had similar attentional demands, and therefore yielded similar error rates and pupil dilations. The lack of difference between these two conditions can be explained assuming that color is a feature mostly processed *pre-attentively* (Treisman & Souther, 1985). Without challenging those studies showing that attention can be critical even for the detection of the so-called pre-attentive features (Joseph, Chun, & Nakayama, 1997), it seems very likely that color discrimination provided much less load on attentional capacity. This interpretation is corroborated by the finding that the *color* dual task yielded lower pupil dilation than the *sound* dual task, despite having the same number of stimuli to be discriminated. Even though it is likely that working memory processes contributed to the pupillary dilation, a simple explanation in terms of response rehearsal cannot account for the observed pattern In contrast, the most parsimonious interpretation of the present set of results is that pupil dilation reflected the attentional preparation required to discriminate, across the same or different modalities, simultaneous stimuli. Attention allocation in our paradigm has the scope of optimizing visual and auditory processing in face of uncertainty about location (lateralized targets) and/or identity (sound/shape/color) of task-relevant stimuli.

Overall, the pattern of results can be explained only assuming that our measures (pupil dilation, and error rate in the primary spatial task) truly reflect attentional load. It has been previously shown that more challenging tasks, such as discrimination, elicit larger phasic dilation than easier tasks like simple detection (Gabay et al., 2011). This fits well with the notion that, of the two modes of activity of the LC–NE system, the one engaged during more demanding tasks is characterized by larger phasic activations and larger pupil dilations (Aston-Jones et al., 1999; Corbetta et al., 2008). Our results extend this finding by showing that the amplitude of pupil dilations precisely mirrors increasing levels of top–down attentional load across discrimination tasks of very different nature, and suggest that the phasic mode of the LC–NE system can be activated at different levels in a flexible way according to task demands. The absence of a main effect of target number (unilateral vs bilateral spatial targets in the primary task) does not support the presence

of a ceiling effect, because the difference was absent even in the single task condition, which elicited the smallest pupil dilation. This finding indicates that pupil dilation depended mostly on task instructions (constant within a block of trials) rather than on trial by trial characteristics of the stimuli presented. We also found no systematic modulation of pupil size at baseline and across task conditions, which suggests that pupil dilation, but not tonic pupil size, is an accurate measure of task difficulty. However, it is also possible that small differences in tonic pupil size, whenever present, were masked by the concurrent effect of other incidental factors such as pupillary hippus or random fluctuations in the level of alertness.

A second aim of the present study was to explore the consequences of increased attentional load upon spatial monitoring and visuospatial awareness. We focused on trials with bilateral targets, which yielded a higher error rate than trials with unilateral targets, in line with the hypothesis of between-hemifield competition in conditions of double simultaneous stimulation (Driver & Vuilleumier, 2001; Kinsbourne, 1977; Miller, Gochin, & Gross, 1993). Although an overall positive laterality index somehow suggested that participants missed more frequently the left target, no significant differences emerged across hemispaces. It is important to note that the hemifield attentional bias seems to be strongly dependent on stimuli parameters, like spatial frequency (Proverbio, Zani, & Avella, 1997) or type of spatial task (Roth & Hellige, 1998), and task demands, like visual short-term memory (VSTM) load (Sheremata, Bettencourt, & Somers, 2010). This dependence on task contingencies might be the source of discrepancies in the literature. Studies using a dual-stream rapid serial visual presentation (RSVP) task reported a left visual field advantage (Verleger et al., 2009; Verleger et al., 2010; Verleger, Śmigasiewicz, & Möller, 2011), which could reflect a specific advantage of the right hemisphere for processing fast-paced sequences of stimuli. In contrast, other studies have shown that the attentional bias at baseline turns into a rightward bias following increased cognitive load (Dodds et al., 2008; Peers et al., 2006) and following decreased arousal and alertness (Bellgrove, Dockree, Aimola, & Robertson, 2004; Fimm, Willmes, & Spijkers, 2006; Manly, Dobler, Dodds, & George, 2005; Matthias et al., 2009; Schmitz, Deliens, Mary, Urbain, & Peigneux, 2011). In our data we did not find any evidence of a modulation of the hemifield bias due to attentional load. One possible explanation is that verbal responses, mediated by the left-hemisphere, could have interfered with the processing of visual stimuli in the right-hemifield: according to the 'functional distance model' (Kinsbourne & Hicks, 1978) the amount of interference in a dual task is dependent upon the distance between the control centers involved in the two concurrent tasks. In other words, tasks that are processed by anatomically close regions are more difficult to perform together (for instance, speaking and using the right hand; Kinsbourne & Cook, 1971). Our multitasking conditions required an additional verbal response, recruiting more resources in the left hemisphere and perhaps weakening visual processing of the stimuli presented on the right. Thus, it is conceivable that the verbal response could have prevented the rightward bias to increase in the dual task conditions, in contrast to other studies that used manual responses (Peers et al., 2006; Pérez et al., 2009). Further studies are required to clarify the relationship between response modality and the direction of the hemifield attentional bias.

In conclusion, our results show that pupil dilation accurately mirror variations in top–down attentional load in a task where bottom-up confounds were kept constant across conditions, thereby supporting and extending the use of this valuable and easy-measurable psychophysiological index. Pupillometry seems to have the potential to be fruitfully implemented in a variety of settings, both experimental and non-experimental. The possibility to record and categorize performance in the absence of an overt response seems particularly promising for an accurate online monitoring of task load or flexible allocation of attentional resources.

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