The pupil dilation response to visual detection

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ABSTRACT

The pupil dilation reflex is mediated by inhibition of the parasympathetic Edinger-Westphal oculomotor complex and sympathetic activity. It has long been documented that emotional and sensory events elicit a pupillary reflex dilation. Is the pupil response a reliable marker of a visual detection event? In two experiments where viewers were asked to report the presence of a visual target during rapid serial visual presentation (RSVP), pupil dilation was significantly associated with target detection. The amplitude of the dilation depended on the frequency of targets and the time of the detection. Larger dilations were associated with trials having fewer targets and with targets viewed earlier during the trial. We also found that dilation was strongly influenced by the visual task.

KEYWORDS: pupil dilation, target detection

1. INTRODUCTION

Pupil size and dynamics are controlled by two synergistic pathways that operate on the smooth muscles of the pupil. The parasympathetic pathway is mediated by the Edinger Westphal oculomotor complex in the midbrain and innervates the sphincter which is the circular muscle responsible for constriction. The sympathetic pathway, mediated by the hypothalamus, innervates the radial dilator muscle of the iris responsible for dilation[1]. Sympathetic excitation causes of pupil dilation. It is also widely documented that mental events inhibit the Edinger-Westphal nuclei thus causing the relaxation of the sphincter muscle, contributing to the dilation of the pupil[2,3]. Visceral, somatic and olfactory sensory information are all relayed to the hypothalamus and converged onto the efferent sympathetic fiber system. It has been known for centuries, that they elicit a pupillary dilation[1,4-7].

Pupil size and dilation have been studied in relation to cognitive processing of visual information, and pupil dilation responses have been recorded at visual detection threshold[8]. More importantly, their data indicated that the neuronal mechanisms underlying the pupil light reflex were less sensitive than those mechanisms controlling the dilation, i.e. although the pupil constricts in the presence of a light, at lower light stimulations and when the task is to detect the light, the pupil dilates. More recently, it has been shown that when a subject, involved in visual-motor operations with a computer, gains information about her task and thus changes her point of view, thinks of different goals or modifies her scanpath or the general behavior, this cognitive event (or *task shift*) is correlated with a series of abrupt pupil dilations averaged over a period of time[9]. Task-evoked pupil dilations are reported in the literature[6,10] and the magnitude of the pupillary dilation appears to be a function of the cognitive workload and attention required to perform the task[11,12]. The emotional content embedded in the picture might also trigger, and be proportional to, the pupil dilation reaction; very aversive or pleasant pictures are associated with large dilations[13]. Other important studies on the correlation between attentional demand and pupil diameter have been conducted[14-16].

Visual search is a complex set of component processes that may be compartmentalized into two interleaving phases of scanning and detection. Eye movements drive the fovea to fixate each part of a scene to enable processing with high resolution. Each fixation involves bottom-up signal processing and top-down higher-level operations such as semantic binding and symbolic association of visual memory, which are basic to recognition[17-18].

The main objective of this study was to examine whether the simple appearance and detection of a specific object in a visual search task triggers a pupil dilation. Other variables considered are the frequency or density of targets in the image

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sequence used as the stimulus and the time of the detection with reference to the start of the sequence. We know that habituation or adaptation can, in theory, affect the sensitivity of a particular sensory modality when the same stimulus is repeated and thus its probability increased (for example the P300 in EEG[19]) and we wanted to verify if the same type of phenomenon occurs during visual detection for the pupil dilation.

Subjects were asked to attend to a sequence of images and to report, with a key press, the detection of a specific object, or target. In the first experiment, visual targets were not explicitly defined; the meaning of the object but not the specific object itself was explained to the subjects; we called this *semantic* visual detection. In the second experiment, targets were well defined and easy to discriminate; we called this *iconic* visual detection. In all of the experiments, pupil dilation was significantly associated with target detection. The amplitude of the dilation depends on the target frequency and how early in the experiment the targets appeared.

2. METHODS

Experiments were designed to examine the pupil responses associated with object detection under visual search conditions with limited image viewing time. Experiments were performed in moderate light conditions so that the pupil operated approximately in the middle of the iris muscle length-tension curve where the relationship between excitation and amount of muscle response is linear. This was to avoid the mechanical muscle saturation at the two extremes of the pupil size where significant amount of input excitation may generate undetectable pupil responses. Eye blink artifacts, (see example in Figure 2) as reported by the eye tracking system, were automatically removed from the pupil data and the corresponding affected parts of the pupil record were recovered with cubic interpolation. It is known that pupil break frequency is approximately 1-2 Hz[20-21]. Pupil data was accordingly low-passed with a Butterworth filter with a cutoff frequency of 4Hz.

2.1 Experiment 1: semantic target detection

Subjects: The ten subjects who participated in the experiment ranged between 25 and 50 years old and had no particular training in viewing the type of images and image presentation used in this study.

Apparatus: Eye movement data were used to verify the locus of the viewer's overt visual attention. The Arrington Research fixed system (www.arringtonresearch.com) with a temporal resolution of 60Hz and a pupil size resolution of 0.03mm was used to monitor eye position and pupil size over an extended period of time. Eye movement data were used to verify the locus of the viewer's overt visual attention while pupil diameter was the dependent variable of interest.

Stimuli: Visual stimuli were a series of simple object-icons displayed at the center of the blank white screen. The 17 icons used subtended approximately 2 degrees of visual angle at a viewing distance of 30cm (Figure 1). The group of visual icons contained two objects that could be easily associated with a threat; a skull and cross-bones and a bomb. The other stimuli (fifteen in total, Figure 1) were neutral objects, easily discriminable from the two targets, as indicated by the very small rate of false alarms.

Procedures: Participants were instructed to look at the center of the screen, trying not to blink and were asked to identify objects that could be associated with a meaning of threat or danger. Subjects had to press a button upon object identification. The icons (target and non targets) were randomly displayed every 0.7 seconds for 100 consecutive intervals; each icon was maintained in the center of the screen for the entire period and then immediately replaced with the next icon. Image sequences were randomized and targets time and number of occurrences varied among different sessions and they ranged between two and six appearances per trial; the presentation of a target was disabled for three consecutive presentations after each target presentation; this was to prevent the chance that two targets were presented sequentially or within a limited temporal distance. Each subject participated in only one session.

2.2 Experiment 2: iconic target detection

Subjects: Seven trained imagery analysts participated in this phase of the research.

Apparatus: We used the EyeLink 1000 head supported eye-tracker system (www.eyelinkinfo.com) that has a temporal resolution of 1000Hz and a pupil size resolution of 0.01 mm. Eye movements and pupil data were collected.

Stimuli: Stimuli were wide area high-resolution gray-level satellite photos of urban and rural areas divided into a sequence of about 3000 non-overlapping image "chips" of 500x500 pixels each subtending approximately 10 degrees of visual angle. Image chip presentation was much more rapid, and thus the task more challenging, than Experiment 1 and 2. The WinVis stimulus delivery software (www.neurometrics.com/winvis) ensured presentations free of frame drops, recorded behavioral responses and provided synchronization pulses to align the EEG, eye and pupil tracker and button press data with stimulus presentation[22]. Image chips were presented in rapid serial visual presentation, RSVP, at 10 Hz (100 msec/chip) at a screen refresh rate of 60 Hz. This time is usually sufficient for human observers to complete sophisticated object discrimination[23]. Most of the viewing session lasted 120 seconds (1200 image chips) with 2-3 sessions per satellite photo though we also performed some longer experiments of about 3-4 minutes of viewing. The target chips contained a helipad centered on a chip and usually located atop a large building in an urban setting. Figure 1 shows sample target and distracter image chips. A small fixation marker was present during the image presentation sequence. The frequency of image chips containing helipads varied from session to session and they ranged between 0.016Hz (very low density, an average of one target every 62 seconds) and 1Hz (very high density, an average of one target every second) of the entire number of stimuli used in each session.

Procedures: Viewers were asked to fixate the fixation point in the center of the monitor during image presentation and to promptly communicate with a button press the presence of helipad targets (see example in Figure 1). The seven viewers repeated the experiment at least thirty times which were divided, for most of the viewers, into two separated session days. Each trial was characterized by its target frequency and the image chips composing a sequence were always unique, although sequences for different trials could have been extracted from the same large satellite photo. Image chips were centered on the screen in a constant gray background which maintained the baseline pupil size in the low-middle range of 3-4 mm for all subjects. Subjects performed the experiment in a small wooden and sound-proof booth in our lab isolated from the rest of the environment; inside the booth there was a chair and a desk with the stimulus monitor and the eye-tracker apparatus. Each trial was preceded by a few minutes of rest during which the subject could sit back and relax.

Illumination function estimation: Light continuously enters the pupil system. In Experiment 2, the brightness fluctuation of the large stimulus might have generated some pupillary response that we needed to differentiate from the visual detection-driven dilation. In order to do so we wanted to estimate the amount of light perceived at the retina. The screen luminance was calibrated with a photometer located at the distance of the subject's face during the experiment. Each image chip was pixel by pixel multiplied with a 2D Gaussian foveal spatial mask with a standard deviation of 1 degree of visual angle and mean positioned in the center of the image. The spatial integration of all pixel gray levels in the Gaussian masked image (expressed in Lux) approximated the amount of light perceived by the retina for that particular image; assuming, of course, that the locus of eye fixation, and thus the fovea, was maintained at the center of the image. The temporal progression of image chips thus created a sequence of these foveal brightness intensity values which defined a temporal illumination function that was finally low-passed for our analysis using the pupil bandwidth parameters discussed above in this Section. The illumination function was then cross-correlated with the pupil function and used to characterize our visual targets in terms of light stimulation.

3. RESULTS

The raw pupil diameter as a function of time revealed the typical random fluctuations often referred to as pupil unrest. This physiological fluctuation is correlated between the two eyes and is also correlated to brain activity[24]. Nevertheless, a pupil area expansion is often detectable right after a target is shown to the subject as shown Figure 2.

Short segments of pupil data were extracted from the long raw pupil vector (as reported for example in Figure 2) for each target presentation and then classified into two groups depending on the occurrence of the button press. A target was considered *hit* if it was followed by a button press within one second from the presentation; a *miss* was a target with no button press detected during that period of time. One second is a reasonable overestimation for the reaction time of a button press; in a preliminary psychophysics study with no pupil recording but the same visual detection task, we measured an averaged reaction time of 470msec and all button press fell within a second; many studies in the literature report similar values, ranging between 300 and 550 msec depending on the complexity of the visual discrimination[25].

Each pupil segment was shifted along the vertical axis so that the initial pupil diameter at the time of the target presentation was zero. The average of the segments, across subjects and viewing sessions, showed a significant dilation starting about 500 msec after target presentation. This was true for both experiments. See the temporal location of the onset of the averaged pupil dilation in all panels (Figure 3). Error bars indicate upper and lower bounds of the confidence intervals for the average pupil profile, with alpha=0.01 and assuming that the pupil diameters are normally distributed within each error bar bin. Pupil dilation is statistically significant when the error bars do not cross the abscissa (see plots, Figure 3). The visual task was easy in Experiment 1, thus viewers detected all the targets. For the second experiment, where targets were often missed (an average of about 23% of the time), we classified data traces as *hits* and *misses* (Figure 3, right panel, blue plots are *hits* and red plots are *misses*). Pupil dilation was significant for all hits. When the target was missed, pupil dilation was reduced but still significant in most cases.

We further divided data in Experiment 2 into four more specific categories corresponding to, i) trials with lower density of target (0.1 – 0.5 Hz, Figure 3, right panel, top-left pair of plots), ii) trials with higher density of targets (0.5 – 1 Hz, Figure 3, right panel, top-right pair of plots), iii) targets viewed within the first half of a single trial (bottom-left pair), iv) and targets viewed within the second half of the trial (bottom-right pair). We found that the average amount of dilation is lower in trials with high target frequency and is also decreased toward the end of the experiment. These results provide evidence that habituation affects the sensitivity of the pupil dilation when viewers are repeatedly exposed to the same visual target. The largest dilations were measured for experiments with very few targets or for those targets presented only a few seconds after the beginning of the experiment (Figure 4) where the factor of surprise was obviously stronger. Again, error bars indicate confidence intervals for alpha=0.01. Notice that the lower bounds of the pupil dilation confidence limits are above zero except for very high target density trials above 0.8 Hz (Figure 4, left) and for target presented very late in the trial (Figure 4, right); which means that for these target presentation conditions the corresponding dilations were not significant.

The amplitudes of the dilation were very small, usually in the range of a few tens of millimeters and the latency of the dilation onset was widely distributed between 300 and 700 msec. The average shape of the dilation was characterized by an initial steep dilation followed by a slow recovery to the initial tonic level (Figure 3).

The light pathway must be involved in the mechanism and although the ambient illumination was constant throughout the entire viewing session, the computer monitor illumination entered and stimulated the retinal parasympathetic pathway and may affect the pupil size. This factor was controlled explicitly in Experiment 1, and likely played a limited role in Experiment 2 with small stimuli. In the second experiment however, the 10 Hz rapid sequencing of such a diversified range of large photos likely generated a pattern of illumination correlated with pupil size. The two signals, pupil diameter and illumination, were cross-correlated and all the resulting cross-correlation functions, for all viewing sessions, were averaged into one single cross-correlation function; a very distinct peak of negative correlation was, indeed, found at around 400 msec phase lag (Figure 5). This is what one would expect since an increase of illumination decreases pupil size. The lag of 400 msec is in agreement with what has been reported in a previous experiment[26] for similar experimental mean light levels.

Might this light component have biased our results? That is, could the observed dilation have been triggered by a repeated decrease of image illumination? We first compared the foveal brightness between all target and non-target image chips and we did not find a significant difference. We then looked at the derivative of the illumination function during the experiment at the onset of each stimulus presentation. A negative value of the derivative indicates a decreasing step of illumination whereas a positive value indicated increase brightness. The distribution of derivatives, for target and non-target images, were not significantly different, their means respectively 0.058 Lux/sec and 0.035 Lux/sec and p=0.65 which indicated that there was not a significant illumination bias in any of the stimulus groups. Nevertheless in many of the conditions a very small and sometime significant pupil constriction was observed just after the target presentation and leading the major incoming dilation (Figure 3, see Discussion).

Button presses were used in our experimental protocol to discriminate those targets that were explicitly recognized and reported by the viewers, from targets that subjects might have only detected semiconsciously or that were not clear or strong enough to be unequivocally recognized and, thus, to promptly trigger a motor response. Button presses however, might have conditioned the cognitive and attentional engagement that subjects felt about experiment. If no button presses wer required, that is if subjects had no specific visual task in mind, subjects might not have devoted to the presence of a target in the field of view the necessary significance and importance and the pupil might have responded with a different behavior. We asked three of our subjects to repeat part of the second experiment using the same type of stimuli and experimental protocol but without the button press requirement. These three subjects were just instructed to look at the dynamic scene being aware that it was similar to what they already viewed earlier during the other (with button press) measurements and simply keep a mental count of the detected targets. We found that pupil dilations in this condition were indeed very small. A summary of the different conditions is reported in Table 1 and Figure 6. The average dilation for *hit*, target detections reported by a button press, was larger and lasted longer than the average dilation for *miss*, targets not reported by any button press (*miss*) but presented in trials where button press was required. For those trials where the button press were not required, the pupil did not seem to respond with the same intensity that we observed in the other conditions.

4. DISCUSSION

It has long been known that the pupil dilates in response to emotion evoking stimuli. Pupil size and pupil dilation have been studied in relation to mental workload and the overall state of alertness and pupillography has been successfully employed in monitoring psycho-cognitive activity in many perception experiments such as speech or word recognition, reading and simple auditory tests. Here, we posed the question in vision perception: whether and how the pupil dilates when a target or an object of interest is detected and recognized by the visual system.

We designed two experiments characterized by different amounts of visual difficulty. Viewers were asked to attend to a sequence of scenes and to recognize a specific target. In the first experiment, stimulus presentation rate was slower and the targets were easy to discriminate from non-targets. Subjects were informed only about the general meaning of the object they had to detect, a symbol of *threat* or *danger*, and not about its specific name or iconic conformation. We called this *semantic* visual detection since the experiment required a rapid visual inference where each stimulus had to be recognized and semantically elaborated. This type of condition is commonly encountered during natural viewing conditions where stimuli must be often perceived and interpreted based upon a specific context or cognitive task. Experiment 2 was the most challenging, with satellite imagery of urban and rural areas displayed in a rapid sequence (10 Hz). The helipad targets were univocally characterized by clear visual features, an open white paved space signed with a *H*, and they were well explained to the subject. We called this *iconic* visual detection.

A significant pupil dilation resulted after the target presentation with the onset of the dilation ranging between 300 and 700 msec (Figure 3). We measured how this dilation varied as a function of target density and the time of target presentation in the trial and found that larger dilations occurred both for targets viewed earlier in the trial and for those trials with fewer target presentations. Habituation, surprise, or uncertainty, are well-known factors in neuropsychology and may all be involved in the progressive decrease of perceptive sensitivity due to repetition of a stimulus. The importance of uncertainty have been reported in other pupil studies; for example in auditory perception, the amount of pupil dilation for target recognition was found to be increased for less probable sound targets[27] and it was found to be in general proportional to the learning of the stimulus[28]. Our experiments demonstrated the same phenomenon in case of visual detection.

We noted a small constriction, especially in Experiment 2, just subsequent to the presentation of a new stimulus and anticipating the larger opposite dilation movement. We checked the non-target pupil responses in Experiments 1 and 2 and we noted the same characteristic but without the dilation (Figure 3). They cannot be light-triggered constrictions as the visual stimuli were isoluminant; moreover, a step-wise light function defined by a sequence of stimuli having different levels of brightness, would not generate the same type of consistent and repetitive constrictions in the pupil as we observed. We know that the pupil responds to non- luminosity stimulus attributes such as, for example, spatial frequency[29]. Thus, the transition between two different stimuli might generate a spatial frequency transient able to trigger a small pupil response which is immediately overcame by the opposite and stronger movement of the dilation driven by the slower sympathetic limbic system. This is particularly true in the first experiments (Figure 3, left panel) where the sequence of stimuli shown to the subjects was slower and within the pupil operative bandwidth. It is in an interesting phenomenon that will require more specific experiments to be better understood.

Pupil dilation to emotional or visual stimuli is principally controlled by the sympathetic limb of the autonomic nervous system that originates in the hypothalamus. The limbic system is reciprocally connected to the visual pathway in the cortex in a complex manner and the pupil dilation is an interesting mechanism triggered by the visual recognition pathway. The cortex can also exercise a direct influence on the pupil through direct projections to the parasympathetic Edinger-Westphal nucleus in the midbrain[29]. Thus a visual target could, in principle, be semiconsciously recognized in the visual pathway but not reported by a motor response whose initialization occurs later and further back in the frontal motor area. Such a target would be *missed* because the viewer did not explicitly report it, but it could be still able to trigger, implicitly, a limbic/pupil dilation response. We looked at the second experiment where the subjects generated several misses and we found that the average pupil profile after a miss was, indeed, characterized by a weak, but significant, pupil dilation (Figure 3). The finding of a significant dilation for target events not detected by the subject and thus reported with a button press is one of the most surprising findings of this study.

In the control experiment, when we asked some of the subjects to repeat the experiment without the requirement of the button press, we found that the pupil did not respond with the same intensity. This was interesting (although a similar behavior has been discussed in the literature[1]); both in case of a missed target and during the no button press control experiment there was no motor initialization of the arm/hand key press movement; the viewer remained still after the target presentation without showing a sign of the detection. Yet, in case of misses in the main experiment, we observed pupil dilation. The reason might be in the visual task that was substantially different between the two conditions. In other words, a button press was not a necessary condition for the dilation but the definition of button press as a task for the viewer enhanced the level of cognitive engagement the subject had to maintain, in turn affecting the sensitivity of the pupil to target detection.

Several major findings emerge from this study. The human pupil responds with dilation for visual recognition events. The amount of dilation is small and not always detectable at high stimulus presentation rate but becomes a more reliable measure at lower frequencies. The type of visual task given to the subjects influenced significantly the pupil sensitivity and the corresponding response to target detection.

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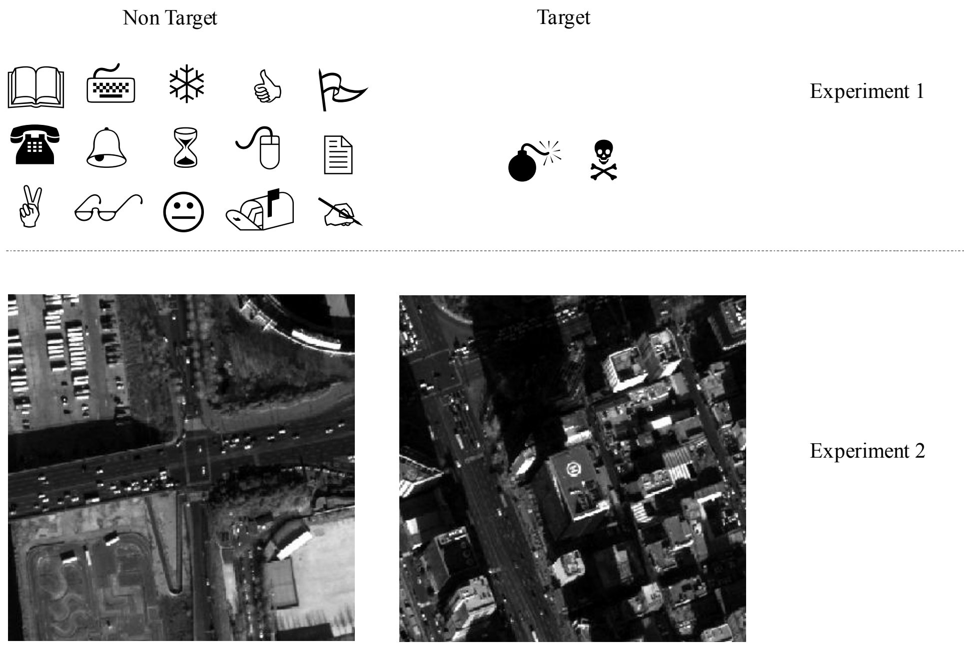


Figure 1. Examples of target (right) and non-target (left) visual stimuli for the two experiments; note the helipad sign in the center of the satellite photo for the second experiment (Experiment 2 imagery is © DigitalGlobe). The locus of eye fixation was maintained at the center of the computer stimulus monitor and stimuli were rapidly alternated at 10 Hz. Subjects were asked to detect objects that could be associated to a meaning of *threat* or *danger* in the first experiment and to detect helipads in the second experiment.

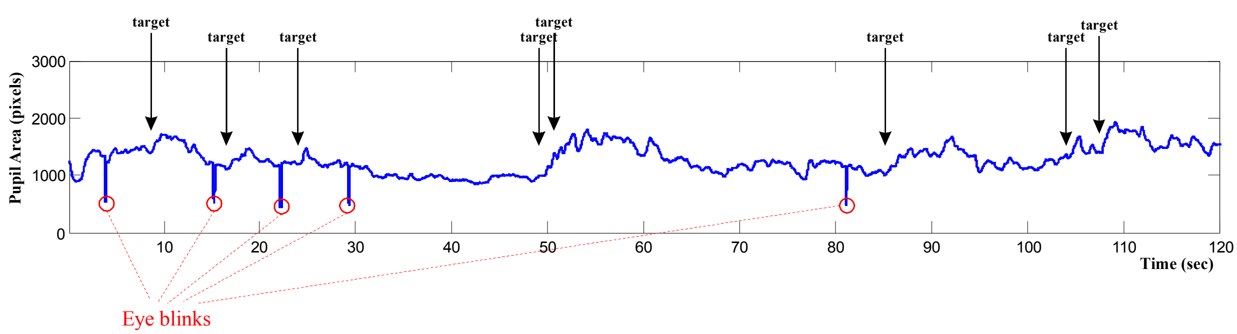


Figure 2. Example of pupil fluctuation during a single viewing session; eye blinks were easily detected by the eye-tracker software and removed in our analysis. Target presentations elicited pupil dilation; see arrows and the associated pupil area expansion.

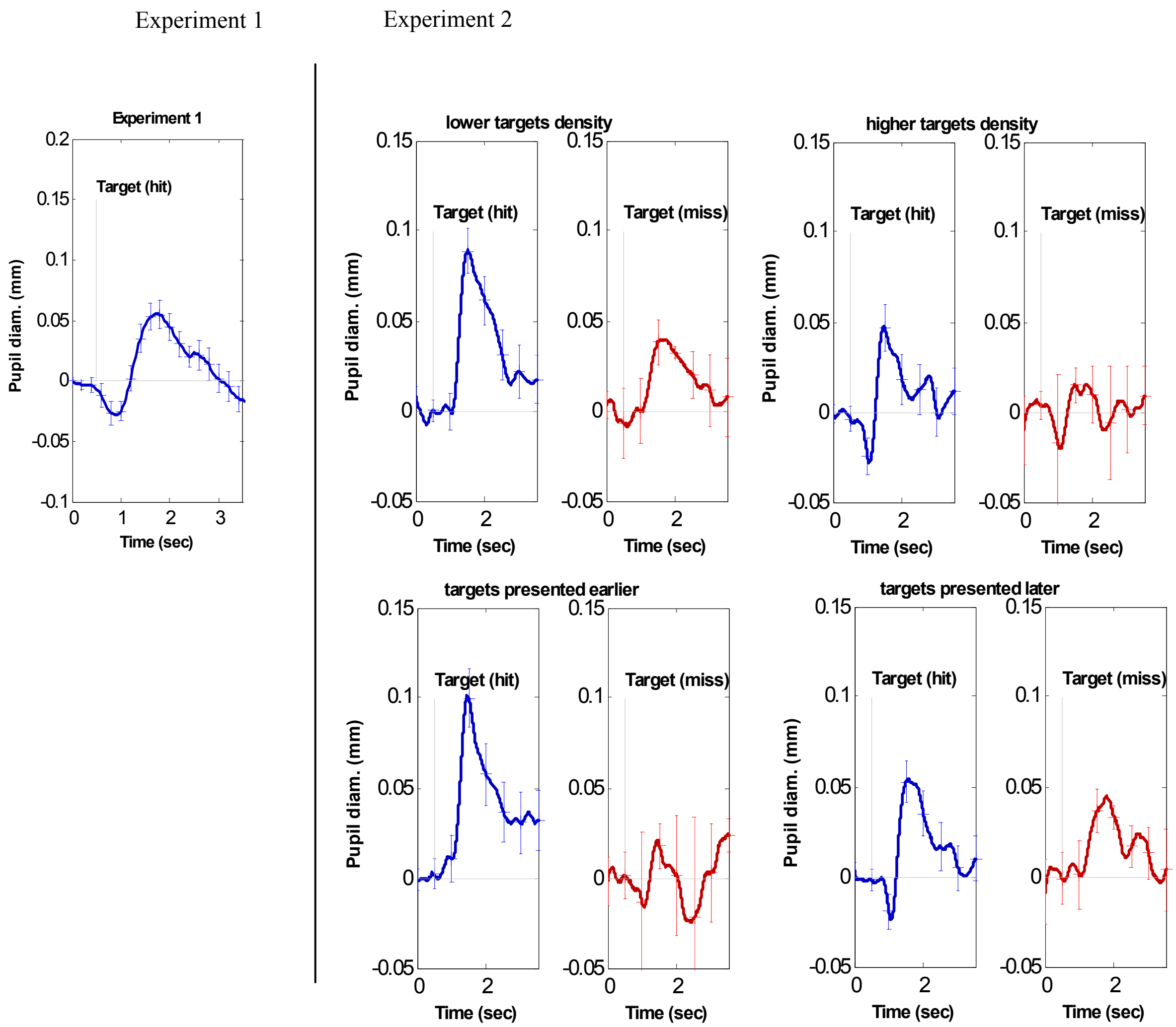
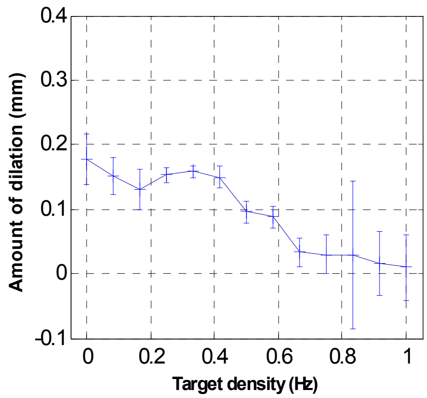


Figure 3. Average of pupil responses for Experiment 1 (left) and Experiment 2 (right). The vertical gray line indicates time of target presentation. Error bars correspond to CIs at alpha=0.01. Pupil dilation onset occurs around 500ms after target presentation in both experiments. For Experiment 2 (right), the data are divided into two groups. In the upper panels, one is for lower targets density (few targets per run) and one for higher targets density (many targets per run). *Hit*, (blue line) are pupil profiles when the corresponding target was detected by means of a button press and *miss*, (red line) are the pupil profiles when the target was missed. Pupil dilation is evidenced by a positive peak of the pupil diameter after the target presentation and it is more pronounced in those runs with fewer targets. In the lower panels, data are divided based on the time of target presentation within the run. Targets viewed earlier generated larger dilations.



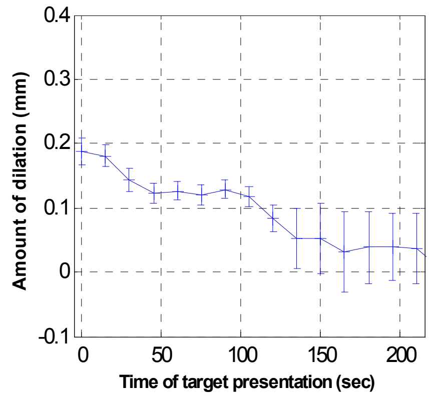


Figure 4. Amount of pupil dilation as a function of target presentation frequency or target density (left) and time of target presentation within the trial (right).

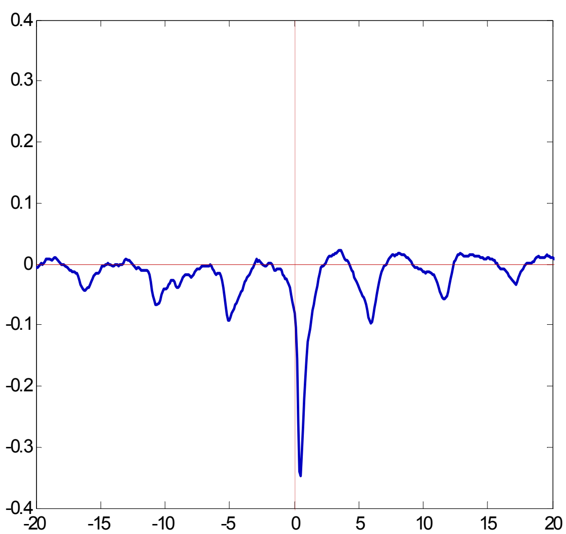


Figure 5. The cross-correlation (averaged for all subjects and viewing sessions) between the computer monitor illumination function (as defined by the foveal sequence of image chips used as visual stimuli) and pupil size, reveals a negative peak at approximately 400 msec phase lag. This is what one would expect; increase of illumination corresponds to decrease of pupil size. The negative (absolute minimum) peak at lags of 400 msec is in agreement with previous experiments on the phase velocity characteristics of the pupil system conducted in similar conditions of background illumination. Notice the periodicity in the cross-correlation function generated by the difference of luminance across the entire satellite photo. Photos of coastline for example often include large dark regions corresponding to the open ocean area. Stimulus chips were presented in a lawnmower fashion and this generated a low frequency pattern of illumination and pupil oscillation.

average dilation	onset of dilation	duration of dilation	viewing instructions
0.066 mm	0.53 sec	1.69 sec	target detected by button press
0.024 mm	0.55 sec	1.45 sec	target missed by button press
0.008 mm	0.61 sec	0.40 sec	button press not required

Table 1. The amount and the characteristic of pupil dilation for different viewing instructions and target presentations: i) viewers were asked to report the detection of a target with a button press and the target was successfully detected; ii) viewers were asked to report the detection of a target with a button press but they missed to do so; iii) button press was not required; viewers were instructed to look at the dynamic scene and simply count all the viewed targets.

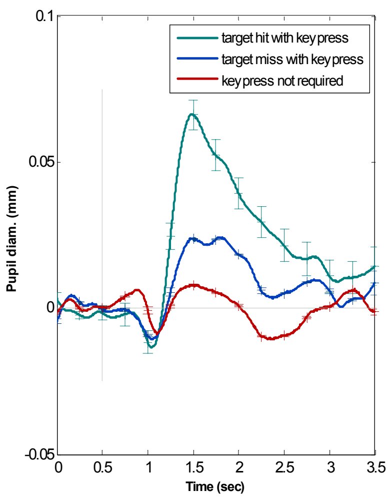


Figure 6. The average pupil dilation for the three separate conditions as defined in Table1.