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Boris I. Gramatikov
Kristina Irsch
David Guyton

Optimal timing of retinal scanning during dark adaptation, in the presence of fixation on a target: the role of pupil size dynamics

Boris I. Gramatikov,* Kristina Irsch, and David Guyton

Johns Hopkins University School of Medicine, Wilmer Ophthalmological Institute Laboratory of Ophthalmic Instrument Development, The Krieger Children's Eye Center, Pediatric Ophthalmology and Adult Strabismus, 600 N. Wolfe Street, 233 Wilmer Building, Baltimore, Maryland 21287-9028, United States

Abstract. While validating our newly developed vision screener based on a double-pass retinal scanning system, we noticed that in all patients the signals from the retina were significantly higher when measurements were performed within a certain time interval referenced to the initial moment when the lights were dimmed and the test subject was asked to fixate on a target. This appeared to be most likely attributable to pupil size dynamics and triggered the present study, whose aim was to assess the pupillary “lights-off” response while fixating on a target in the presence of an accommodative effort. We found that pupil size increases in the first 60 to 70 s after turning off the room lights, and then it decreases toward the baseline in an exponential decay. Our results suggest that there is an optimal time window during which pupil size is expected to be maximal, that is during the second minute after dimming the room lights. During this time, window retinal diagnostic instruments based on double-pass measurement technology should deliver an optimal signal-to-noise ratio. We also propose a mathematical model that can be used to approximate the behavior of the normalized pupil size. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JBO.19.10.106014](https://doi.org/10.1117/1.JBO.19.10.106014)]

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1 Introduction

While validating our newly developed vision screener^{1–3} based on a double-pass retinal scanning system, we noticed that in all patients the signals from the retina were indisputably significantly higher when measurements were done at least 20 s, but not more than 2 to 3 min after dimming the lights and asking the test subject to fixate on a target. This appeared to be most likely attributable to pupil size dynamics and triggered the present short study.

Pupil size can directly affect the amount of light that reaches and is returned by retinal structures in double-pass measuring technology, such as retinal birefringence scanners,^{1,2,4} scanning laser ophthalmoscopes,⁵ scanning laser polarimeters,⁶ optical coherence tomography (OCT) devices,⁷ and other retinal scanning systems.⁸ Since retinal illuminance is proportional to the area of the entrance pupil,⁹ the signals obtained by such retinal scanning systems from the light reflected from the retina can strongly depend on pupil size. A number of investigators have reported the relationship between luminance and pupil size.¹⁰ Yet, these publications use a steady state (after adaptation), ignoring pupil dynamics, and do not mention the influence of accommodation. Numerous publications also describe the acute “lights-off” effect and the slower dark adaptation,¹¹ but there appears to be very little information on how pupil size changes in the first several minutes after ambient lights are turned off and while the subject is fixating on a target, which are usually the

conditions when double-pass systems are used. It is known that both fixation and accommodative efforts cause pupil constriction, eliminating some peripherally entering rays and masking high-order monochromatic aberrations. But, the interplay between this phenomenon, known as accommodative pupillary constriction,^{12,13} and the competing, or rather counteracting pupil dilation due to dark adaptation, is not well studied.

The goal of this study was to determine the extent and more importantly the timing of pupil size changes, and to potentially find a time window during which the pupil size is expected to be maximal, to allow the best conditions for obtaining information from the retina at maximum signal-to-noise ratio (SNR).

2 Methods

We recruited 10 test subjects, age 28 to 60, none of them were on any medication affecting pupil size, and all properly consented. After a period of 10 min of room-light adaptation, the subjects were asked to fixate on a white-light accommodative target (a red dash with a white border, 3×1.5 mm, optically 33 cm from the eye). The target was front-on illuminated constantly by a faint electric bulb, providing background luminance in the area of the target of about 1×10^{-2} cd/m², just enough to enable the test subject to fixate. The ambient illumination was turned down immediately after initiation of the recording, from 27 to 2×10^{-3} cd/m². Pupil diameter was measured under monocular conditions (with one eye occluded) by means of an eye tracking apparatus¹⁴ using video oculography and comprising an infrared-sensitive USB video camera (240 × 320 pixel resolutions; Web Digital Camera, Hong Kong) equipped with a 12-mm fixed-focal-length lens (Fig. 1). Near-infrared illumination of

*Address all correspondence to: Boris I. Gramatikov, E-mail: bgramat@jhmi.edu

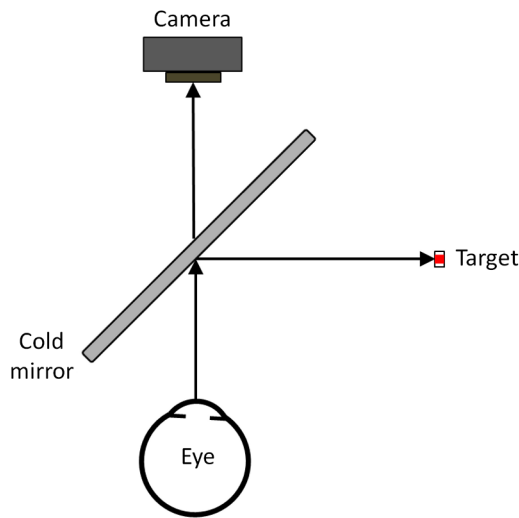


Fig. 1 Optical setup used to measure the pupil size.

the pupil was provided by an infrared light emitting diode (OD-50L, 880 nm; Opto Diode Corp., Inc., Newbury Park, California). The camera was connected to a desktop computer that displayed the incoming stream of frames and controlled the video frame capture using custom acquisition software written in MATLAB® (MathWorks, Inc., Natick, Massachusetts). We used image acquisition with a frame rate of 5 fps, with continuous recording. The recorded eye's image sequences were analyzed off line. Pupils were approximated with circles, and their diameters were calculated with commercial eye tracking software (IRIS; Chronos Vision, Berlin, Germany). Pupil detection uses edge detection and the Hough transform to identify a circle in a parameterized space.^{15,16} Blinks were detected as abrupt drops of more than 30% in pupil diameter, lasting for 200 to 400 ms, and were replaced by the preceding value. Pupil area was calculated based on the diameter measured from each frame. In order to compare pupil behavior across test subjects and possibly derive a general trend, the pupil area traces were normalized as

$$A_n(t) = \frac{A(t)}{A(0)}, \quad (1)$$

where $A(t)$ is the area measured in time, $A(0)$ is the baseline value at the initial moment when the light was turned off, and $A_n(t)$ is the normalized area. Of the 10 subjects recorded, only five managed to maintain both arousal and fixation during the first 6 min of measurement, as determined by the video monitoring. The data from the uncooperative subjects were excluded from analysis.

3 Results

Figure 2, upper trace, shows the normalized trace from one subject as pupil area versus time, plotted over 6 min (360 s) after the lights were turned off, with the subject not accommodating. Figure 2, lower trace, shows the same type of curve from the same subject, now accommodating. Figure 3 shows the normalized traces of all subjects studied.

In addition to the individual traces, the average trace is also shown (thick line). The dilation reaches its maximum, with area ca. 70% above the baseline level, at a time of about 60 s. Then, the average normalized curve starts descending exponentially toward the baseline.

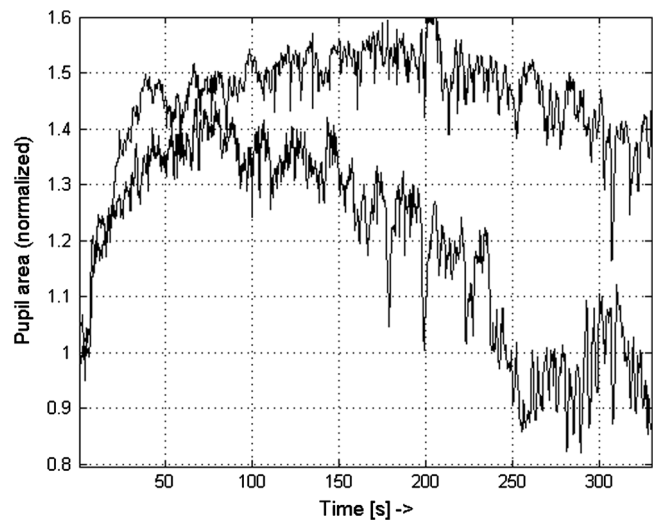


Fig. 2 Pupil dynamics during dark adaptation. Upper trace: without accommodation; lower trace: with accommodation on a target.

The averaged normalized trace was then approximated in MATLAB using a nonlinear least-squares regression fit with the following model function

$$A_n(t) = (1 - e^{-a_1 t})e^{-a_2 t} + 1, \quad (2)$$

where the time t is in seconds. For the fit, it was assured that the estimated coefficients fell into the 95% confidence interval using the Jacobian of Eq. (2), returned by the fit. The coefficients calculated from the averaged curve were, respectively, $a_1 = 44.2 \times 10^{-3}$ and $a_2 = 6.3 \times 10^{-3}$. The corresponding approximated curve is plotted on Fig. 3 as a dashed line.

4 Discussion

Although this study has not investigated specific groups of patients, it has shown that there is a definite pattern in the change of pupil size during dark adaptation and in the presence of an accommodative effort. However, there were marked intersubject variations in pupil size progression over time, as can be seen in

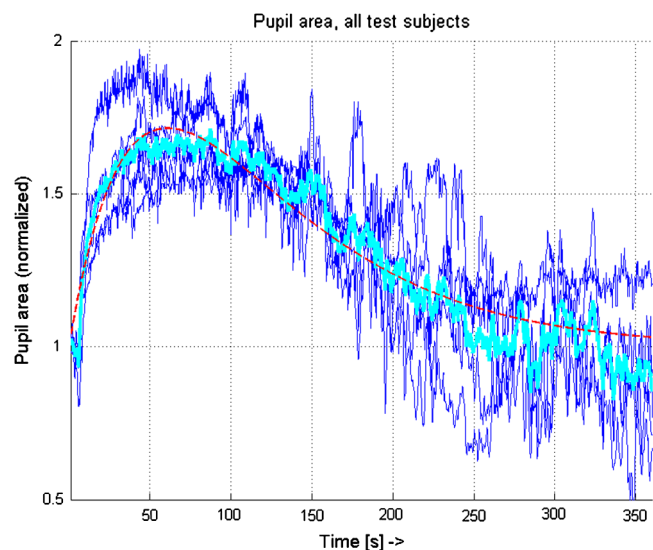


Fig. 3 Normalized pupil area of all subjects studied under accommodating conditions. The averaged normalized trace is shown as a thick line. The dashed line shows the exponential fit of the averaged curve.

Fig. 3. We think that the first and foremost cause for this was the different level of accommodation provided by the different subjects, and in the lowest trace—partially because of lack of arousal. The different ability to accommodate, which is age dependent, may account for the variance observed. Another cause for variance may have been the use of an imperfect target, which was small but probably lacked enough detail. There is also the direct effect of age on pupil size. One study showed that pupil diameter slightly increases across age groups between 1 and 19 years,¹⁷ while other studies have reported that pupil size becomes smaller in an almost linear manner with increasing age.^{18,19} Other studies have shown that pupil size can also be affected by the level of arousal,²⁰ the transient allocation of attention during which the pupil shows transient dilation,^{21,22} a type of stress reaction.²³ Yet, since our study deals with the progression of relative changes with respect to a light-adapted baseline, we believe that we have observed a clear pattern of a relatively fast initial increase, and then a slower decrease in pupil size, as long as the arousal factor was controlled and fixation was present.

This study was quite challenging because of the difficulty encountered by the test subjects when trying to stay fixated over 6 min and at the same time to maintain arousal. With the limited number of subjects, this study is merely a proof of concept. Investigating the presence or absence of accommodation, intersubject variability, age-related variability, and day-to-day variability of pupil size dynamics by means of analysis of variance is expected to shed more light on the phenomenon studied, and may lead to more precise criteria for the optimal timing of retinal scanning during dark adaptation. Of interest, a study by Bradley et al. showed that gender and iris color have no significant effect on the dark-adapted pupil diameter.²⁴

The mechanisms involved in the “lights-off” response are mainly the parasympathetic relaxation and sympathetic activation¹¹ causing dilation. The mechanism involved in accommodative pupillary constriction is quite different, involving changes in the accommodative state via the convergence–accommodation mechanism. The extent of influence of each of these mechanisms, and hence the location in time of the maximum pupillary size found by us, might well be influenced by the variable factors mentioned above, which warrants further investigation.

Algorithms may be developed for adjusting the coefficients of the exponential fit a_1 and a_2 in accordance with valid variability factors, so that the software in retinal scanning instrumentation may suggest the best possible time window for acquiring data with maximum SNR.

5 Conclusion

We observed a certain variance between the plots, most likely attributable to a different level of accommodation attempt for the different subjects. Yet, when accommodation attempt was present, the pupil size followed a specific pattern—a sudden increase, followed by a relatively flat peak, then an exponential decay toward the baseline. Based on the signal traces in Fig. 3, it can be concluded that measurements between 22 and 130 s after dimming the lights are likely to be performed with a pupil area at least 50% larger than the baseline. The pupil size appears to be maximal at about 60 s after “lights off.” This should be taken into consideration when optimizing the time window for measurements on retinal structures with double-pass systems when subjects are fixating on a target. The optimal time window for the measurements, according to these results, is during the second minute after dimming the light.

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Biographies of the authors are not available.