Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

Pupil dynamics with periodic flashes: effect of age on mesopic adaptation

BÁRBARA SILVA,[1] ANA SFER,[2] MARCELA A. D'URSO VILLAR,[3] LUIS ALBERTO ISSOLIO,[1] AND ELISA M. COLOMBO[1,*]

[1]*Instituto de Investigación en Luz, Ambiente y Visión (ILAV), CONICET-UNT, Departamento de Luminotecnia, Luz y Visión (DLLyV), Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucumán (UNT), Av. Independencia 1800 (4000) Tucumán, Argentina*
[2]*Cátedra de Probabilidad y Estadísticas, Departamento de Matemáticas, Facultad de Ciencias Exactas y Tecnología, Universidad Nacional de Tucumán (UNT), Av. Independencia 1800 (4000) Tucumán, Argentina*
[3]*Cátedra de Bioestadística, Facultad de Medicina, Universidad Nacional de Tucumán (UNT), Lamadrid 875. PB (4000) Tucumán, Argentina*
**Corresponding author: bsilva@herrera.unt.edu.ar*

Received 7 April 2016; revised 7 June 2016; accepted 10 June 2016; posted 14 June 2016 (Doc. ID 262568); published 0 MONTH 0000

The purpose of this study is to determine the pupillary dynamics with periodical flashes from a peripheral glare source, in similar conditions to night driving, while focusing on dependence with age. We measured two groups of people: youth and adults. Maximum pupil size decreases due to periodic flashes. Latency does not present significant differences. The reduction of pupil size is greater for older adults. The presence of a peripheral and periodic glare source modifies the pupil size. This leads to a reduction of retinal illuminance, which is greater for older adults.

OCIS codes: (330.4595) Optical effects on vision; (330.7320) Vision adaptation; 330.7323..

http://dx.doi.org/10.1364/JOSAA.99.099999

1. INTRODUCTION

Change in pupil size is one of the adaptation mechanisms used by the visual system when there are changes in the luminance of a scene. When the pupil contracts, due to the presence of a glare source, there are two simultaneous effects. There is loss in the quantity of light that reaches the retina, that is, of the retinal illuminance. There also is an improvement in the quality of the retinal image. This is due to the reduction of aberrations and the increase in the depth of focus [1–3]. Both of these effects affect the visual response. For this reason, the estimation of the pupil size and its dynamic is often desirable. The information about the behavior of the pupil is important for evaluating the reduction of the visual functions in different conditions of everyday life.

This is particularly important in the study of the effects of sources of glare on night driving. Mesopic adaptation has been of interest in several previous works. Specifically, the measurements of visual efficiency in foveal and peripheral vision [4–6], together with the evaluation of the brightness of the scene with transient [7,8] and steady glare [9], have been studied. In studies such as these, it is necessary to know the pupil size in order to be able to interpret the results.

A previous investigation regarding pupil size [10], in the mesopic range ($0.5\ \mathrm{cd/m^2}$) and for just one glare source, showed the stability of the latency time. It had taken into account different levels of glare characterized by the photopic illuminance measured at the cornea (15, 30, and 60 lux) and a range of ages between 19 and 53 years old [10]. Ellis [11] studied the changes in pupil light reflex while increasing the luminance in photopic levels [10]. On the other hand, the age, as a factor affecting light-adapting pupil size was one of the variables well studied by Winn *et al.* [12]. It is well established that the maximum pupil size in steady adaptation is smaller in elderly adults. This is a condition known as senile miosis. Bitsios *et al.* [13] studied resting pupil diameter, constriction velocity, and other parameters such as scotopic and photopic levels of adaptation. The authors found differences in the results from the different age groups.

In the case of night driving along motorways, the visual system is usually subjected to sequences of multiple flashes. This has peaked our interest in the study of the dynamics of the pupil diameter. We are particularly interested in its dependence with age.

The hypothesis of this paper is that, when periodic flashes occur, the diameter of the pupil does not recover its initial value. Furthermore, the reduction, which modifies the state of visual adaptation, is greatest in older adults. For this reason, we have studied the pupil dynamics when observers' eyes are exposed to sequences of dazzling flashes. We did this while taking into account different adaptation luminances and glare illuminance.

2. METHODOLOGY

The experiment consisted of registering changes of pupil diameter while the subject was watching a cross. At the same time, a glare source was being periodically turned on and off. A program developed in MATLAB generated the white fixation cross. The cross was generated at exactly 4 deg in the center of a display (32.5 cm by 24.5 cm). An eye tracker camera (Eyetracker ViewPoint) was synchronized with the control of the glare source. We reported the size of the eye's entrance pupil the way most studies do. We used the virtual image of the physical pupil as seen through the cornea.

The glare was generated by means of an incandescent lamp, which was located at 10 deg from the line of sight of the subject and at the same height as the fixed cross. This generated an illuminance value of 60 lux, which was measured over the cornea of the subject's right eye. The subject's pupil size was registered, and the adaptation was binocular. The time of the glare presentation was controlled by means of an electronic shutter with an aperture of 1.5°.

The subject's head was fixed on a chin rest at a distance of 2 m from the display. We took into account the results obtained by Radhakrishnan and Neil Charman [14]. These authors have shown that there is no accommodative miosis when the distance of accommodation is greater than 1 m. The time adaptation to the background luminance was 5 min. Figure 1 shows the layout of the experiment.

The subject had to look at the fixed cross during the session. There were no blinking restrictions. The glare was turned on for 0.5 s at 5 s intervals. The total sequence for each value of background luminance (0.1, 0.2, and 0.5 cd/m^2) had 30 flashes. In this study, we follow the standard practice of specifying stimulus intensities by photopic luminance. We even included light levels in the mesopic range.

The camera systems registered the changes in the pupil diameter with a frequency of 30 Hz. Figure 2 shows a typical temporal reply of the pupil size to a transient glare. This is shown for each period as well as the magnitudes that are determined.

The pupil diameter is represented as a function of time (units are arbitrary).

- **DP** diameter of the pupil that corresponds to the generic time t.
- $\mathbf{DP_{MAX}}$ maximum diameter of the pupil before the constriction.
- $t_{\mathbf{MAX}}$ initial time immediately before the contraction of the pupil starts.

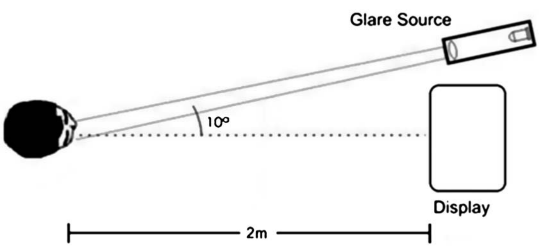

Fig. 1. Experimental setup.

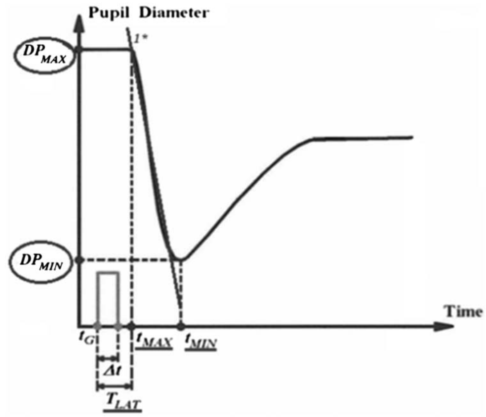

Fig. 2. Pupil light reflex of a transient glare.

- $\mathbf{DP_{MIN}}$ minimum diameter of the pupil on contracting.
- $t_{\mathbf{MIN}}$ time at which the maximum constriction of the pupil occurs.
- t_G time at which the glare turns on.
- Δt time interval during which the glare is on.

Furthermore, latency time ($T_{\mathbf{LAT}}$) is calculated from these parameters. Latency time is the interval that occurs between the start of the glare and the moment when the pupil constriction begins. The velocity of fall of the pupil diameter also is calculated from the abovementioned parameters ($V_{\mathbf{FALL}}$):

$$T_{\mathrm{LAT}} = t_{\mathrm{MAX}} - t_G, \tag{1}$$

$$V_{\mathrm{FALL}} = \frac{\mathrm{DP_{MAX}} - \mathrm{DP_{MIN}}}{t_{\mathrm{MAX}} - t_{\mathrm{MIN}}}. \tag{2}$$

Twenty subjects were split into two groups. One group was made up of 10 adults aged 22 to 30 years old (mean age: 26.1 years old; SD: 2.6 years) and is referred to as the "Young" group. The other group consisted of 10 adults aged from 51 to 59 years old (mean age: 53.4 years old: SD: 3.2 years) and is referred to as "Older Adults." Both groups consisted of four women and six men. During this experiment, no refractive correction was used. The criterion for inclusion was the absence of visual illnesses or deficiencies.

3. RESULTS

For each subject and for each adaptation luminance, the pupil diameter was registered during the sequence of 30 glare flashes. Figure 3 shows an example of the register carried out for an observer and for a value of adaptation luminance. For each period of a register, we determined the values of the maximum diameter of the pupil as the mean of register values during latency time. We also extracted the minimum value, which was expressed in millimeters. The latency time was expressed in milliseconds, and the velocity of fall of the pupil diameter was expressed in millimeters per second.

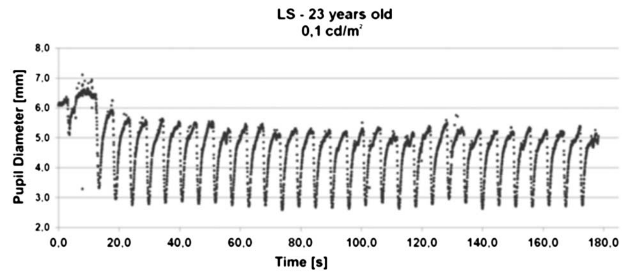

Fig. 3. Pupil diameter as a function of time for observer LS (23 years old) and for 0.1 cd/m^2.

A. Resting Pupil Diameter ($DP_{MAX\,0}$)

The initial pupil diameter for all subjects was determined as the mean of those obtained before the first flash. These were obtained in steady conditions of adaptation for each adaptation luminance presented in the display (0.1, 0.2, and 0.5 cd/m^2). The mean values of $DP_{MAX\,0}$ and their standard deviations for each adaptation luminance are separated by age group and are shown in Fig. 4. Young and older adult data have been displaced in the horizontal axis in order to better differentiate between the two data sets.

An ANOVA shows that the effect of background luminance on the pupil diameter is not statistically significant ($F_{2,54} = 0.75$, $p = 0.4768$). This could be due to the small range of luminance considered (only a part of the mesopic range). On the other hand, the effect of age on the pupil diameter is statistically significant. For example, resting pupil diameter decreases with age ($F_{1,54}0.98$, $p < 0.0001$). This phenomenon is well known and could be explained by senile miosis [12].

B. Latency Time (T_{lat})

The latency time was calculated for each subject, for each adaptation condition, and for each pulse of glare. This means that we obtained 1800 values. Doing a multilevel analysis, we found no differences regarding the age ($z = 0.92$; $p = 0.356$) nor the repetitions of glare flashes ($z = -1.02$; $p = 0.307$). The background luminance was the only significant variable affecting latency time ($p = 0.001$). Due to these results, we applied a Tukey test. We considered the mean latency time for each background luminance (Fig. 5), and we found the effect of the adaptation luminance is not significant. This is probably because of the small range considered for the continuous variable as well as the remarkable variability introduced by the subject (34%).

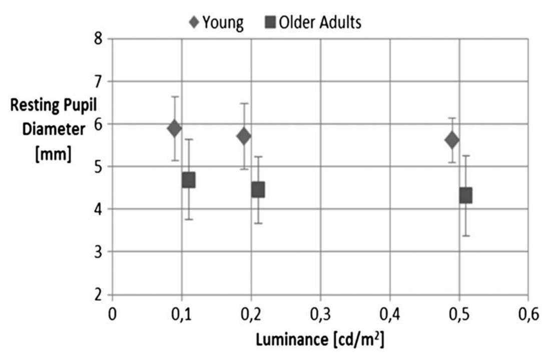

Fig. 4. Mean resting pupil diameter (DP_{MAX0}) as a function of the background luminance for young and older adults. Each error bar corresponds to mean square error.

C. Velocity of Fall

The velocity of fall of the pupil diameter is the speed at which the pupil is reduced when it responds to the glare. Using multilevel analysis, we obtained that the only significant effect produced by age is ($z = -3.74$; $p < 0.001$). The variability between subjects is 58%. Because we did not find dependence on time or on luminance, we calculated the mean velocity of fall for each age group (Fig. 6) to quantify the difference due to age.

If we consider Eq. (2) for this computation, it is possible to explain the difference between older adults and young adults by looking at the smaller differences between DP_{MAX} and DP_{MIN} in older adults. These differences are due to senile miosis, while the denominator remains constant.

D. Maximum Pupil Diameter

We will analyze the maximum for each PLR because it will give us the measure of the dynamics of the process. It also will lead us to answering whether or not there is a lower value after the repeating process. Figure 7 shows the parameter DP_{MAX} for each subject and for each luminance level over time. The different curves of DP_{MAX} for each adaptation luminance can be seen (inside each plot). The different curves of DP_{MAX} for the different ages can be seen (between columns). DP_{MAX} has, in

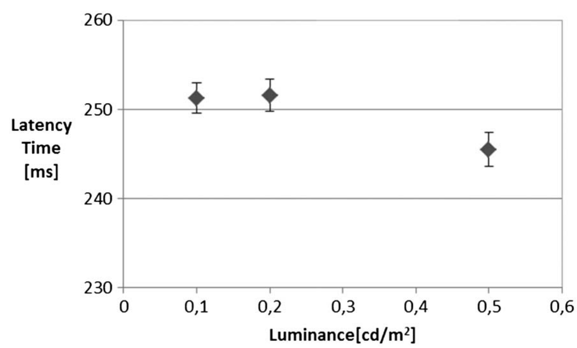

Fig. 5. Mean latency time for the three background luminances considered. Each error bar corresponds to standard deviation.

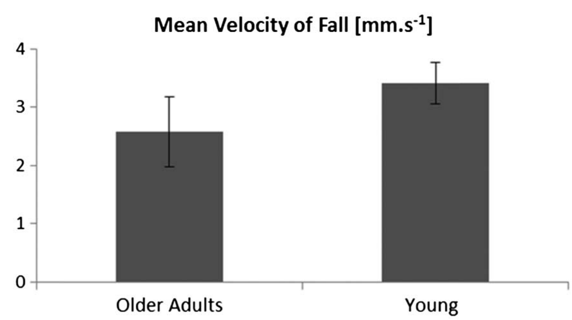

Fig. 6. Mean of velocity of fall for each age group. Each error bar corresponds to standard deviation.

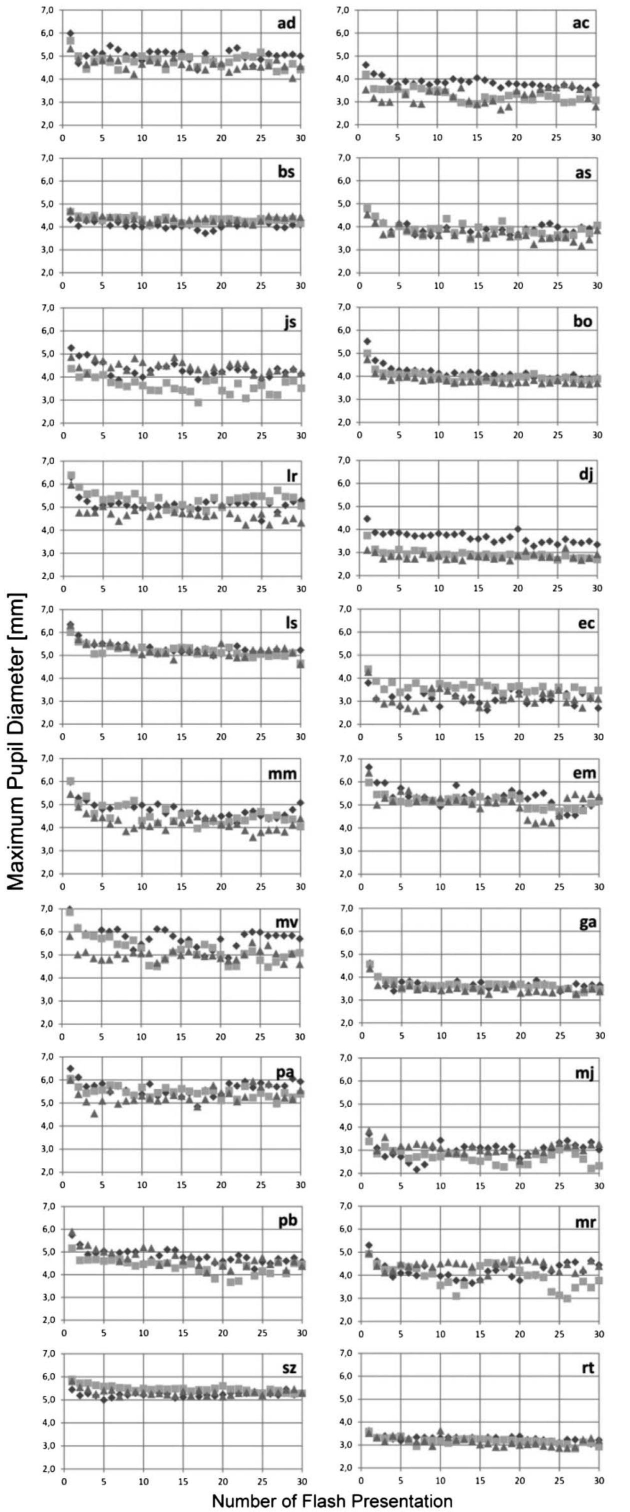

Fig. 7. Sequence of the maximum pupil diameter for each subject for the three values of the background luminance: Young group (left) and Older Adult group (right). (◆) 0.1 cd/m^2, (■) 0.2 cd/m^2, and (▲) 0.5 cd/m^2.

general, higher values with lower dispersion for young subjects than for older ones. Also, it is interesting to note the presence of a pattern of behavior that is repeated in the two age groups: the maximum pupil diameter reduces following approximately an exponential function, and the intercept depends on the subject.

In this longitudinal study, we proposed a generalized linear mixed model (GLMM) to consider the absence of independence among the DP_{MAX} values over time. The study includes the influence of age and luminance in this trend as well as the variation due to subjects. The GLMM is an extension of generalized linear models obtained by introducing random effects in the model. The random effects account for correlation between repeated measurements within each subject and the variation between subjects. In a GLMM, it is assumed that the correlation between repeated observations comes from each subject because they share the same random effect (subject). 5
However, they are assumed to be conditionally independent 6
given the random effect. In this sense, the GLMM proposed model considers two levels of variation: the number of flash presentations and the subject, along with two more factors: age and luminance. It also assumes a random effect due to the subject and an exponential shape due to the response on the number of flash presentation of each subject accounting for age and luminance level (the variable is normalized for each subject, with his resting pupil diameter DP_{MAX0}).

This analysis shows that the fixed effects—luminance, age, and number of flash presentation—are all statistically significant (luminance 0.2 cd/m^2 $t = 9.19$; luminance 0.5 cd/m^2 7
$t = 11.39$; age $t = 3.75$; flash $t = 15.1$; $p < 0.0002$). If we consider the base category as young for age, we find that an individual aged between 50 and 60 years will have on average a DP_{MAX}27% lower than that of a subject of 20 to 30 years for the same luminance and number of flashes. If we consider the base category for luminance as 0.1 cd/m^2, on average the value of DP_{MAX} for luminance 0.5 cd/m^2 will be 4% lower than for the luminance of 0.1 cd/m^2. This is similar for background luminance 0.5 cd/m^2 and 0.1 cd/m^2. The value on mean DP_{MAX} decreases when the number of flashes grows.

Figure 8 shows the fitted DP_{MAX} on the observed trajectories by age and level of luminance equal to 0.1 cd/m^2, 0.2 cd/m^2, and 0.5 cd/m^2. The DP_{MAX} fitted follows an exponential shape and is lower for adults along all the number of flashes.

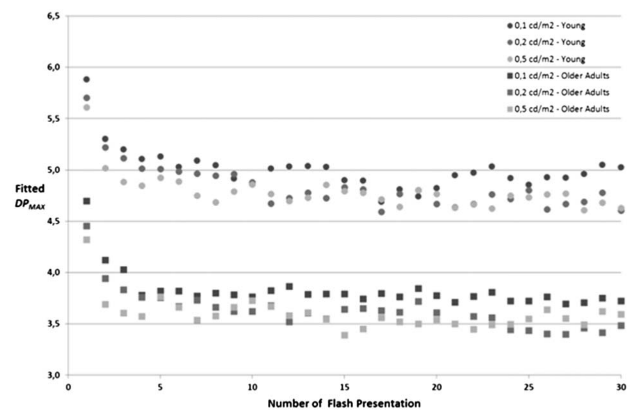

Fig. 8. Fitted maximum pupil diameter for each age group for the three values of the background luminance 0.1 cd/m^2, 0.2 cd/m^2, and 0.5 cd/m^2.

The DP_{MAX} fitted for the flash presentations number 1, 15, and 30 for each age group and each luminance level are shown in Table 1. The DP_{MAX} average decreases approximately 5% (between 0.1 and 0.5 cd/m^2) luminance levels in the youth group and 4% in the group of older adults. Within the younger group, the mean DP_{MAX} decreases between 9% and 10% between the first flash and the last. Within the group of adults, this percentage is equal to 7%. At the first flash in the group of adults, the mean DP_{MAX} is approximately 28% lower than the young group for three luminance levels. For the last flash (number 30), the percentages are equal to 27% (luminance 0.1 cd/m^2), 26% (luminance 0.2 cd/m^2), and 25% (luminance 0.5 cd/m^2). In the same table, the average resting pupil diameter was included for each age and adaptation luminance.

According to the result of the Shapiro–Wilk test, $p = 0.889$, it can be concluded that the random effects follow a normal distribution and the residuals are randomly distributed around zero.

E. Retinal Illuminance

Retinal illuminance is a measure of luminous radiation that reaches the retina and is calculated as the following [3]:

$$E_r = 0.0036 \cdot L \cdot S_p \cdot \tau. \quad (3)$$

In Eq. (3), L is the luminance of adaptation expressed in cd/m^2, S_p is the area of the pupil in mm^2 and τ is the transmittance of the ocular media. Given that the area of the pupil is a function of its diameter (DP), L is a constant, and τ depends on the subject, the Eq. (1) is

$$E_r = k \cdot DP^2, \quad (4)$$

where k is a constant that depends on the subject.

Given that we have already determined the average initial resting maximum pupil diameter-DP_{MAX0}-, and we also have calculated the fitted final value-DP_{MAX30}-(Table 1), for each age range and for each adaptation luminance (Fig. 4); then it is possible to calculate the ratio between the final and initial retinal illuminance. A given proportionality for each age range and for each adaptation luminance can be considered using the following equation:

$$\frac{E_{r30}}{E_{r0}} = \left(\frac{DP_{MAX30}}{DP_{MAX0}}\right)^2. \quad (5)$$

Results from this calculation are shown in Table 2.

Table 1. Adjusted Values of DP_{MAX} [mm] for Glare Flashes Number 1, 15, and 30 and the Mean Resting Pupil Diameter DP_{MAX0} [mm]

Age Group	Luminance [cd/m^2]	DP_{MAX0} [mm]	DP_{MAX1} [mm]	DP_{MAX15} [mm]	DP_{MAX30} [mm]
Youth	*0,1*	5,88	5,18	4,92	4,67
	0,2	5,71	4,94	4,7	4,47
	0,5	5,61	4,89	4,65	4,43
Older Adults	*0,1*	4,7	3,7	3,56	3,43
	0,2	4,45	3,57	3,45	3,32
	0,5	4,32	3,54	3,42	3,3

Table 2. Ratio of Retinal Illuminance for Each Age Group with Corresponding Background Luminance

Groups	Background Luminance [cd/m^2]	$\frac{E_{r30}}{E_{r0}}$ %	Average $\left(1 - \frac{E_{r30}}{E_{r0}}\right)$ %
Youth	0,1	63	38
	0,2	61	
	0,5	62	
Older Adults	0,1	53	44
	0,2	56	
	0,5	58	

One can observe that in both age groups there is a reduction of retinal luminance, and on average a younger subject received a 38% less retinal illuminance after 30 glare flashes. This value worsens to 44% for an older adult.

4. DISCUSSION

The most important conclusion in this paper is that the periodic presence (0.5 s at 5 s intervals) of a glare source (60 lux at 10° from the line of sight) produces a pupil size decrease over time. This tendency varies according to the range of ages considered, the background luminances, and the subjects. This leads to a reduced retinal illuminance. The mean reduction is 38% for the younger group and 44% for the older adults.

We also observed that the chosen mesopic adaptation, which was the resting pupil diameter measured for the older adults (mean age 53.4 years old), is smaller than the value corresponding to the referred group of young subjects (mean age 26.1 years old). The variation between maximum and minimum for the young group is from 4.77 to 6.29 mm and for the older adults is from 3.24 to 5.14 mm–, with $p < 0.001$ ($F = 36,08$). Our results about resting pupil diameter are consistent with those obtained by Bitsios, Prettyman, and Szabadi [13], who considered three adaptation luminance level—one scotopic and two photopic—and also found a difference between young people (mean age 19.5 years old) and older adults (mean age 69 years old). Our mean resting pupil diameters obtained under mesopic condition are somewhat larger than those obtained in photopic conditions, although they are much lower than o get in the darkness. Winn *et al.* [12] also studied the changes that take place in the pupil according to different ages. The authors used a group of subjects whose ages ranged from 17 to 83 years old, along with several photopic adaptation luminances. The aforementioned authors concluded that, under these conditions, the pupil diminishes linearly with age. These results also confirm the previous findings of Feinberg and Podolak [15]. In our experiment, the adaptation luminance does not affect the resting pupil diameter ($p = 0.260$; $F = 1,38$). This is probably because the three values are within the low mesopic range [16].

We compared our resting pupil diameter data with the results of applying Watson and Yellot's model [17] and used our experimental conditions (luminance, age, size of the field, and binocular vision). We found that the remarkable differences may be due to the extrapolation of the model to mesopic levels. On the contrary, if we consider the Moon

Table 3. Resting Pupil Diameter Data for Young and Older Adults (Columns 2 and 4, Respectively), Pupil Diameter Computed According to Moon and Spencer Model (Column 3) and with the Age Correction Purpose for Watson and Yellot (Column 5)

Background Luminance [cd/m^2]	Young	DP [mm] Moon and Spencer Model	Older Adults	DP [mm] Moon and Spencer Model Corrected for Older Adults
0,1	5,88	6,04	4,70	4,92
0,2	5,71	5,72	4,45	4,80
0,5	5,61	5,26	4,32	4,72

and Spencer [18] model [Eq. (5)] based on the background luminance, and if we take into account that adaptation and field size are constant, then we find a good fit of pupillary sizes for the three adaptation luminances in young subjects (Table 3):

$$PD = 4.9 - 3\tanh(0.4 \log L - 0.00114). \quad (6)$$

As this model does not take into account the age factor, it does not adequately reflect our performance for the older adults. However, if we apply the correction for age proposed by Watson and Yellot [17] [Eq. (5)], a reasonable agreement for this group of subjects is achieved (Table 3):

$$PD(L, a, y, y_0, e) = D_{MS} + (y - y_0) * S(L, a, e). \quad (7)$$

In this equation, D_{MS} is the pupil diameter computed with the Moon and Spencer [18] model, and S is the function proposed by Watson and Yellott [17]. This function describes the change in pupil diameter as a function of luminance (L), area (a), age (y), a reference age (y_0), and number of eyes (e).

In the case of latency time, our results are within the same range found by Kardon and Thompson [1] which was –200 to 450 ms-. Bitsios *et al.* [13] and Feinberg and Podolak [15] also found variations similar to those found in this study and used a large number of glare flashes. Ellis [11], who also worked with sequences of glares, found that latency times decreased when stimulus intensity strongly increased from 500 to 220 ms. As in our case, the glare intensity remained constant, and we varied background luminance only slightly. The latency time variation was not significant.

In reference to the velocity fall, the differences found in the present work between young and older adults are in the same direction as those obtained by Bitsios *et al.* [13]: young people present higher velocities than older adults. However, our data are lower than the data obtained by these authors because we calculate a global velocity fall of the pupil diameter taking into account the slope between the maximum and minimum pupil diameter, and these authors compute the maximum rate of fall, which is the slope at the beginning of the change. This was generally somewhat greater than what we estimated. Ellis's [11] study of the fall velocity did not find differences with the different levels of adaptation in the photopic level. We did not find differences with the different levels of adaptation either.

5. CONCLUSIONS

The variation of maximum pupil diameter as the flashes follow one another showed nonlinear behavior, and the fit proposed confirmed our hypothesis that the pupil diameter decreases with age, the level of glare received, and the number of flashes. We know this because the result of these variables is statically significant. An individual aged between 50 and 60 years has a mean DP_{MAX}27% lower than that of a subject of 20–30 years for the same luminance and number of flashes. On average, the value of DP_{MAX} for a luminance of 0.5 cd/m^2 is 4% lower than for 0.1 cd/m^2. Similarly, for the luminances 0.2 cd/m^2 and 0.1 cd/m^2, the value of mean DP_{MAX} decreases when the number of flashes grows. The presence of successive peripheral glare sources in mesopic adaptation conditions reduces the maximum and minimum pupil diameter. Older adults stabilize more quickly, but with a lower value than young subjects. This leads to a bigger reduction of retinal illuminance for the older adults. Latency time is greater for the older adults, which also is the case for fall velocity of pupil diameter.

Funding. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) (PIP 11220090100308); Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT) (PICT 1920).

Acknowledgment. We thank volunteer subjects and the Department of Lighting, Light and Vision (FACET-UNT) for the use of its equipment.

REFERENCES

1. R. Kardon and H. S. Thompson, "The pupil," in *Adler's Physiology of the Eye* (2003), pp. 713–743.
2. O. Bergamin and R. H. Kardon, "Latency of the pupil light reflex: sample rate, stimulus intensity, and variation in normal subjects," Invest. Ophthalmol. Visual Sci. **44**, 1546 (2003).
3. J. M. Artigas, P. Capilla, A. Felipe, and J. Pujol, *Óptica Fisiológica: Psicofísica de la visión* (McGraw-Hill/Interamericana de Espa\na, 1995).
4. R. Aguirre, J. Barraza, and E. Colombo, "The effect of glare on visibility depends on spatial frequency," J. Vis. **7**, 259–259 (2007).
5. R. C. Aguirre, E. M. Colombo, and J. F. Barraza, "Effect of glare on simple reaction time," J. Opt. Soc. Am. A **25**, 1790–1798 (2008).
6. R. C. Aguirre, J. F. Barraza, and E. M. Colombo, "The effect of glare on visibility depends on spatial frequency," J. Vis. **7**, 259–259 (2007).
7. L. Issolio and E. M. Colombo, "Brightness for different surround conditions: the effect of transient glare," Percept. Psychophys. **68**, 702–709 (2006).
8. L. A. Issolio, J. F. Barraza, and E. M. Colombo, "Time course of brightness under transient glare condition," J. Opt. Soc. Am. A **23**, 233–238 (2006).
9. P. A. Barrionuevo, E. M. Colombo, M. Vilaseca, J. Pujol, and L. A. Issolio, "Comparison between an objective and a psychophysical method for the evaluation of intraocular light scattering," J. Opt. Soc. Am. A **29**, 1293–1299 (2012).
10. E. Colombo, S. A. Comastri, L. Issolio, and R. Echarri, "Pupil light reflex produced by glare under mesopic adaptation," J. Light Visual Environ. **31**, 70–79 (2007).

14 11. C. J. Ellis, “The pupillary light reflex in normal subjects,” Br. J. Ophthalmol. **65**, 754 (1981).

15 12. B. Winn, D. Whitaker, D. B. Elliott, and N. J. Phillips, “Factors affecting light-adapted pupil size in normal human subjects,” Invest. Ophthalmol. Visual Sci. **35**, 1132 (1994).

17 13. P. Bitsios, R. Prettyman, and E. Szabadi, “Changes in autonomic function with age: a study of pupillary kinetics in healthy young and old people,” Age Ageing **25**, 432 (1996).

14. H. Radhakrishnan and W. Neil Charman, “Age-related changes in static accommodation and accommodative miosis,” Ophthalmic Physiol. Opt. **27**, 342–352 (2007).

15. R. Feinberg and E. Podolak, *Latency of Pupillary Reflex to Light Stimulation and its Relationship to Aging* (Defense Technical Information Center, 1965).

16. Y. He, M. Rea, A. Bierman, and J. Bullough, “Evaluating light source efficacy under mesopic conditions using reaction times,” J. Illum. Eng. Soc. **26**, 125–138 (1997).

17. A. B. Watson and J. I. Yellott, “A unified formula for light-adapted pupil size,” J. Vis. **12**, (2012).

18. P. Moon and D. E. Spencer, “On the Stiles-Crawford effect,” J. Opt. Soc. Am. **34**, 319–329 (1944).

Queries

1. AU: Please check references have been reordered done.

2. AU: Please note as per OSA style, abstract text will be displayed in single paragraph. Hence, please check and confirm.

3. AU: Please clarify what “those” refers to. Did the mean “the pupil diameter” ?

4. AU: Please spell out PLR. The acronym is not necessary since the term is only used once in this text.

5. AU: Please clarify what “they” refers to.

6. AU: Please clarify what “they” refers to.

7. AU: Please ensure that all variables are in italics

8. AU: Did you mean, simply, DPMAX30 ? Without hyphens? If so, please delete the hyphens.

9. AU: Is the N-dash after mm necessary? If not, please delete.

10. AU: Please clarify this sentence. It appears to contain a typo. What is “o”? Did you mean “we” or “one”? If “one” please add “s” to “get”–one gets.

11. AU: Are the hyphens before and after these figures necessary? If not, please delete.

12. AU: The funding information for this article has been generated using the information you provided to OSA at the time of article submission. Please check it carefully. If any information needs to be corrected or added, please provide the full name of the funding organization/institution as provided in the CrossRef Open Funder Registry (http://www.crossref.org/fundingdata/registry.html).

13. AU: Please use a page number range for reference.

14. AU: Please use a page number range for reference.

15. AU: Please use a page number range for reference.

16. AU: Please provide page range for Refs. [14,16,17,21].

17. AU: Please use a page number range for reference.