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The Effect of Retinal Illuminance on the Subjective Amplitude of Accommodation

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Manuscript title: The effect of retinal illuminance on the subjective amplitude of accommodation

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Abstract

Significance statement: We show that the amplitude of accommodation decreases with target illumination even under photopic reading conditions and a constant pupil size. This result provides a basis for clinical approaches that are not based on an optical explanation.

Purpose: We investigated the effect of retinal illuminance on the amplitude of accommodation while the pupil of the eye remained constant.

Methods: The amplitude of accommodation of 10 young subjects (from 20 to 38 years of age) and 10 presbyopic subjects (from 45 to 54 years of age) were measured subjectively through an artificial pupil of 5 mm using a Badal optometer and for four values of retinal illuminance: 222, 821, 2,138, and 5074 Td. Phenylephrine was instilled to all the subjects to ensure that their natural pupil was greater than the artificial one in all experimental runs. Two-way ANOVAs with age and log luminance as covariates were used to check whether changes in amplitude of accommodation with illumination were statistically significant.

Results: In the range of luminances tested, the amplitude of accommodation decreased on average from 6.34 D to 4.35 D in the young subjects, and from 1.69 D to 1.04 D in the presbyopic subjects. Luminance was associated with the amplitude of accommodation in both young and presbyopic groups, with $p < 0.01$.

Conclusions: The reduction in the amplitude of accommodation with target illumination (a phenomenon named *night presbyopia*) under photopic light conditions is not only due to a reduction in the depth of focus as a consequence of pupil dilation; it is strongly affected by the decrease of retinal illumination.

Keywords: accommodation, luminance, retinal illumination, night myopia, night presbyopia.

1 Introduction

2 There has been substantial evidence suggesting that the objective amplitude of
3 accommodation changes with object illumination since the effect was first observed in
4 the 18th century.¹ Maskelyne in 1789² and Lord Rayleigh in 1883³ were the first to
5 describe how their eyes became short-sighted under low illumination conditions. That is,
6 their eyes experienced a myopic shift at night. This now well-known effect is called night
7 myopia. It took some 50 years after Rayleigh for Ferree and Rand⁴ to study
8 systematically the changes in the near point caused by changes in light, and 10 more
9 years for Cabello to quantify the effect of illumination on the amplitude of accommodation
10 (distance from the near point to far point) as a whole.⁵ Cabello coined the phrase *night*
11 *presbyopia* to capture the effect of receding near point that occurred at mesopic and
12 scotopic light conditions.⁵ Figure 1 (data from Cabello⁵ and Otero et al⁶) shows the
13 reduction of the amplitude of accommodation when the target illumination decreases.
14 Otero⁶ later demonstrated that, on average, the accommodative range decreases
15 progressively towards the point of tonic accommodation (dark focus)⁷⁻⁹ when the
16 stimulus gets dimmer.

17 More recent studies report both a myopic shift in distance refractions^{10,11} and reduced
18 accommodation at low light levels.^{12,13} However, as in the studies of Cabello and Otero
19 mentioned above,^{5,6} most of these changes occur at low mesopic and scotopic light
20 levels, below those typically needed for reading text in the modern world.¹⁴

21 Given the fact that the retinal illuminance depends on target's luminance and on the pupil
22 size¹⁵ (also depending on the large-field luminance¹⁶), the changes in near point and far
23 point may have been affected by pupil miosis occurring as light levels change¹⁷ while
24 accommodation takes place.^{18,19} As the pupil dilates, more peripheral optics contribute
25 to the retinal image, and due to the change from positive to negative spherical aberration

26 that accompanies accommodation^{20,21} refractive measures that include the peripheral
27 optics will tend to reveal reduced accommodation relative to measures that employ more
28 paraxial optics.²² However, because of the impact of quantal noise,^{1,23,24} neural sensitivity
29 declines as retinal illuminance is lowered (square root law). Because defocus primarily
30 demodulates the higher spatial frequencies,²⁵ the lowered sensitivity to these high spatial
31 frequencies may also contribute to a failure to accommodate at low light levels.

32 To separate the optical effects produced by the pupil from the neural effects, we have
33 sought to isolate the neural effect on the depth of focus by studying the impact of retinal
34 illuminance on the subjective amplitude of accommodation for a fixed pupil size. In this
35 study, we constrained the light levels to those typically encountered during reading.¹⁴

36 **Methods**

37 Participants

38 Twenty-three subjects ranging from 20 to 54 years of age participated in this study.
39 However, three participants could not finish the experiment due to inability to
40 accommodate, having excessive tearing, or a pupil smaller than 5 mm after the
41 instillation of phenylephrine. The remaining 20 subjects were split into two different
42 groups of 10 each: young subjects with ages ranging from 20 to 38 years and with a
43 mean (\pm standard deviation) age of 25 (\pm 5.3) years; and 10 presbyopes, with ages
44 ranging from 45 to 54 years and with a mean age of 50 (\pm 3.1) years. Prior to testing, a
45 subjective refraction²⁶ was performed by the same qualified optometrist at a luminance
46 of 108.9 (\pm 1.7) cd m⁻². All subjects had a best-corrected visual acuity of 0.0 logMAR or
47 better. The study was approved by the University of Murcia Ethics Committee. All
48 participants gave written informed consent and the study adhered to the tenets of the
49 Declaration of Helsinki.

50 Experimental set-up

51 A custom made Badal optometer with a stimulus controlled by a stepper motor²⁷ was
52 used to vary target vergence in a range of about +10 D to -18 D. The system consisted
53 of two achromatic doublets; one fixed, whereas the other one could be moved (i.e. Badal
54 lens). With this automated Badal system, subjects adjusted target vergence to find their
55 far point and near point subjectively, using a joystick control. The amplitude of
56 accommodation was defined as the difference in vergence between these two positions.
57 Further details about the optical system and the methodology can be found elsewhere.²⁸

58 The entrance pupil of the eye was chosen as the reference plane for the measurements,
59 so that the amplitude of accommodation can be compared among subjects with different
60 refractive errors.²⁹ For this purpose, a camera focusing at infinity and a plane mirror were
61 used, so the iris of the participants could be focused. Amplitude of accommodation

62 calculations took into account that target position was fixed and its distance finite with
63 respect to the subject.

64 Experimental procedure

65 The left eye of all the participants was measured while the contralateral eye remained
66 occluded. The target was a Bailey-Lovie chart placed at 6.95 m from the subject. The
67 target was inverted to account for the inversion introduced by the Badal system.
68 Participants were told to put their chins on a chin rest, and then their refractive error was
69 compensated by placing the prescription obtained in the subjective refraction in the
70 phoropter, which was placed between the Badal lens and the eye, as close to the later
71 as possible. An artificial pupil with a diameter of 5 mm was placed in the phoropter,
72 approximately at 10 mm from the corneal vertex.

73 Each participant took as many preliminary training trials as necessary until they felt they
74 were ready. After this, two drops of 10% phenylephrine were instilled on the participants'
75 left eye, with an interval of 5 minutes. Phenylephrine does not significantly affect
76 accommodation.^{30,31} The artificial pupil was centered with respect to the natural pupil
77 before it was fully dilated. After 40 minutes, and after making sure that the pupil diameter
78 was greater than 5 mm and not reacting to light, the subjective measurements of the
79 amplitude of accommodation started. Different configurations of room lights and the use
80 of two extra incandescent lamps of 500 W were used to generate four different chart
81 luminance levels (nominally, 11.3, 41.8, 108.9, and 258.4 cd m^{-2} , corresponding to a
82 retinal illuminance of 222, 821, 2138, 5074 Td, respectively.¹⁵) The sequence of
83 luminance conditions was random for every subject.

84 Participants were instructed to move the Badal lens up to the furthest possible position
85 in which they were able to see the letters corresponding to 0.0 logMAR visual acuity
86 clearly, following the "objectionable blur" criterion. The specific instructions (given in
87 Spanish) were to search for the farthest point that sustained a "level of blur which you

88 would refuse to tolerate on a full-time basis. The blur has just reached a point at which it
89 is unacceptable.”³² After obtaining the position of the far point, the subjects were
90 instructed to find their near point by bringing the Badal lens as close as possible until
91 they could perceive a maintained and unacceptable blur, with the same criterion as
92 before. Amplitude of accommodation was then obtained by averaging five far point and
93 near point measurements for each subject and luminance condition.

94 Statistical Analysis

95 Even though we designed the experiment to have two clearly distinct age groups, young
96 (amplitude of accommodation ≥ 3 D) and presbyopes (amplitude of accommodation < 3
97 D), the effect of age on amplitude of accommodation was still expected to be very strong
98 within each group, especially on young subjects. We therefore incorporated age as a
99 potential confounder of the effect of illumination on amplitude of accommodation in our
100 models. Therefore, for each age group, a linear mixed-effect model for repeated-
101 measures was performed with amplitude of accommodation as a linear function of age
102 (as confounder), a logarithmic function of luminance (the main explanatory variable) and
103 subject as random effect. We used a logarithmic scale for luminance because its
104 association with the amplitude of accommodation is roughly linear on average (see
105 Results section). The significance level after Bonferroni correction of the repeated
106 measures analyses for both groups was set at 0.025. The package “lme4”³³ for the R
107 statistical environment (<https://www.R-project.org>) was used to estimate the parameters
108 of the linear mixed models. The p -values for the Kenward-Roger modification³⁴ of the F-
109 statistic (an improved small sample approximation) was obtained with the function
110 “Anova” of the R package “car”.³⁵

111 **Results**

112 The mean spherical equivalent obtained for the young group was -0.15 D. The standard
113 error of the mean (SEM) multiplied by 1.96 was 0.68 D. For the presbyopic group these
114 values were -0.10 and 1.11 D. The mean amplitude of accommodation (and 1.96 SEM)
115 obtained for the young group were (in descending order of luminance) 6.34 (0.35) D,
116 5.66 (0.43) D, 5.63 (0.45) D, and 4.35 (0.59) D. Figure 2 shows the amplitude of
117 accommodation for each young subject at all four luminances. Subjects are sorted from
118 younger (top) to older (bottom). Overall, amplitude of accommodation decreases when
119 age increases.

120 The mean amplitude of accommodation (and 1.96 SEM) obtained for the presbyopic
121 group (Figure 3) under different luminance conditions (in increasing order of age) were
122 1.69 (0.16) D, 1.36 (0.16) D, 1.24 (0.20) D, and 1.04 (0.21) D. In general, same
123 tendency between amplitude of accommodation and age can be observed in this
124 group.

125 When averaged among each age group, our results can be summarized in Figure 4. As
126 the illumination increased from 11.3 to 258.4 cd m^{-2} , the far point moved farther away
127 from the eye approximately two times more in the young subjects (0.51 D) than in the
128 presbyopes (0.23 D). In addition, the near point came about three times closer to the eye
129 in young people (1.48 D) than in presbyopes (0.41 D).

130 For the young group, amplitude of accommodation increased with luminance by 1.36 D
131 / $\log_{10} (\text{cd m}^{-2})$ ($p < 4 \times 10^{-5}$) and decreased with age by 0.13 D / year ($p = 0.07$) as
132 estimated with linear random-effect model for repeated measures. For the presbyope
133 group, the estimated increase of amplitude with log luminance was more than 3 times
134 smaller at 0.45 D / $\log_{10} (\text{cd m}^{-2})$ ($p < 2 \times 10^{-6}$). Amplitude decrease with age was similar
135 at 0.11 D / year ($p = 0.01$).

136 **Discussion**

137 The aim of this study was to assess the effect of changes in luminance on subjective
138 amplitude of accommodation over the range of environmental light levels typically used
139 for reading.¹⁴ By employing a fixed 5-mm pupil diameter, these changes in stimulus
140 luminance altered the neural sensitivity of the visual system,¹ but avoided the confounder
141 of optical changes caused by pupil changes. Thus, the only optical changes experienced
142 by the eye were those happening during accommodation, so differences in perception of
143 the target were due to changes in neural effects produced by changes in retinal
144 illumination. In our Badal system, the retinal illuminance changed slightly during
145 accommodation since the image nodal point of the eye changes its position,¹⁵ but that
146 change is less than 5% even for almost 7 D of accommodation.³⁶ A limitation of the
147 present study is the lack of objective measurements of the amplitude of accommodation,
148 which would shed some light on whether or not the lack of light affects the response of
149 the ciliary muscle or if it is just a problem of photon noise.

150 Our results (an approaching far point and receding near point) are in general agreement
151 with previous studies by Cabello,⁵ Otero⁶ and others³⁷. Unlike these previous studies,
152 however, in which light levels and the accommodative response both altered pupil size
153 and therefore the optical characteristics of the image,³⁸ our use of a fixed pupil diameter
154 (5 mm) isolated the impact of changing neural sensitivity on amplitude of
155 accommodation. Thus, our results show that besides optical effects generated by the
156 change in pupil size, retinal illumination plays a key role in the variation of the amplitude
157 of accommodation.

158 In addition to the main effect of presbyopia, the differences found in the magnitude of
159 average changes of the far point with luminance could be explained by the greater
160 transmission factor of ocular media in younger subjects producing a larger retinal
161 illumination in the younger than the aged eye for the same object's luminance. Mean
162 transmittance of 50 years old subjects is approximately 79% that of the 25 years old

163 subjects.³⁹ In relative terms, the effect of the target luminance is similar in both groups,
164 since the younger group accommodated between 3 and 4 times more than the
165 presbyopes, on average.

166 The mean age of the presbyope group was 50 years and previous studies indicate
167 average subjective amplitude of accommodation of an individual of that age is
168 approximately 1.75 D,⁴⁰⁻⁴² which is about 0.4 D greater than the one obtained in this
169 study with a target luminance of 108.9 (1.7) cd m⁻² (similar to that one used in clinical
170 measurements). This difference could be explained by the effect of the depth of focus
171 due to the difference in pupil diameters, since a typical pupil of 50 year olds at these
172 luminance levels is approximately 4 mm,⁴³ 20% smaller than the artificial 5-mm pupil we
173 used here. A similar tendency was found for the younger subjects as for the older ones.
174 The average amplitude of accommodation for a 30-year-old individual is about 7 D,⁴⁰
175 which is larger than the 5.66 D we observed in our younger sample. Significantly,
176 objective measures of amplitude of accommodation⁴⁴ report values of about 6 or 7 D in
177 young adults, and approximately zero in those over 50 years. This discrepancy between
178 the subjective^{40,41} and objective⁴⁴ measures of amplitude of accommodation in older eyes
179 is presumed to reflect the pseudo-accommodation or subjective depth of focus which is
180 incorporated into subjective measures of amplitude of accommodation as used in the
181 present study. Because of large inter-subject differences,^{40,42,45} as well as the sensitivity
182 of subjective accommodation to stimulus and instructions given to subjects,^{32,46} the small
183 differences between the current study and earlier reports is perhaps expected.

184 One main difference between a focused and a defocused image is the amplitude of the
185 high spatial frequency content in the image.²⁵ As retinal illuminance decreases, higher
186 spatial frequencies are affected more by photon noise.⁴⁷ Therefore, the signal indicating
187 defocus^{48,49} becomes less visible as retinal illuminance decreases and accommodation
188 tends to its resting state (around -2 D on average, although it varies a lot from subject to
189 subject)¹³. Luminance reduction is far more impactful under scotopic light levels as it is

190 shown in Figure 1 with a larger jump in the transition between mesopic and scotopic
191 ranges. The current study has shown that a decrease in amplitude of accommodation
192 can occur independently of the change of pupil size and is present at low photopic light
193 levels as well, such as those used in reading,¹⁴ which would be in agreement with
194 Campbell's work on the minimum amount of light required to elicit the accommodation
195 reflex in humans.¹² Campbell stated that "if the luminance of the object is diminished until
196 it approaches the sensory threshold the perception of the less intense blurred edge of
197 the image will become impossible". Therefore, in Campbell's own words "the higher the
198 luminance of the object the easier will be the detection of this out-of-focus blurring, and
199 the greater will become the accommodation response".

200 Our results highlight the importance of light levels in vision, especially in presbyopic
201 patients, when performing near vision tasks, such as reading. For instance, not having
202 enough light could mean that a presbyopic patient may not be able to read at near
203 distances as a consequence of their near point getting further away from their eye due
204 to dim lighting, even when their addition has been properly calculated at photopic levels.
205 Some presbyopia treatments consist of expanding depth of focus by using an artificial
206 small pupil in contact lenses^{50,51} or inside the cornea.⁵² However, this methodology
207 causes a decrease in retinal illuminance, which may alter the patient's near point. In a
208 theoretical study, Xu et al.³⁸ found that, at low light levels, visual function was generally
209 worse when using small-pupil solutions than multifocal solutions.

210 In conclusion, our results show that the retinal illuminance changes that accompany
211 reductions in target luminance reduce the subjective amplitude of accommodation over
212 the stimulus range commonly encountered with text in the modern environment. It is
213 likely therefore that lowered light levels will exacerbate any age related decline in
214 amplitude of accommodation and therefore lower environmental lighting situations may
215 be driving the onset of clinical presbyopia and the age at which optical aids are required.

216 Lighting conditions, therefore, should be taken into account in the assessments,
217 diagnostics and prescriptions performed in the daily clinical practice.

218 **Acknowledgments**

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220 Discussion section.

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Figure Legends

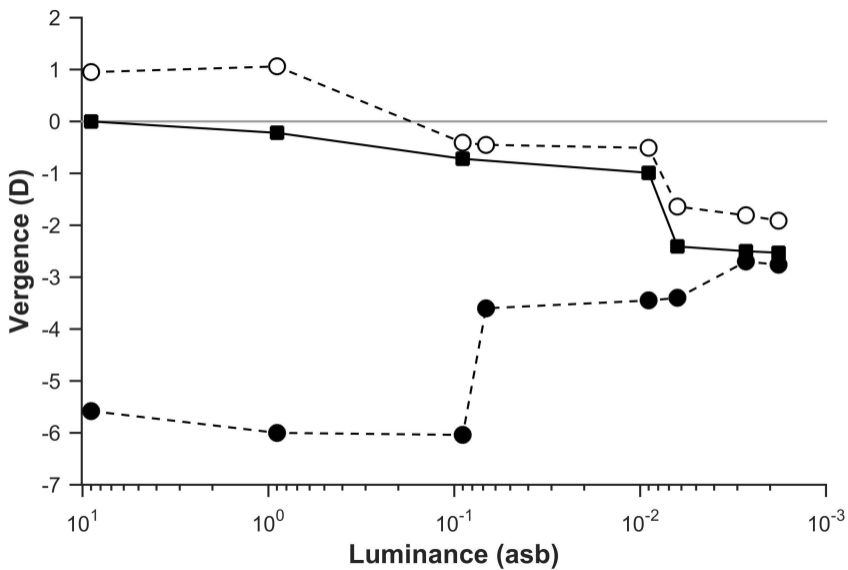
Figure 1. Variation of the subjective far and near points (and thus amplitude of accommodation) as a function of stimulus luminance (open and black circles, respectively). Target vergence producing maximum visual acuity is also plotted (black squares). Luminance is given in Apostilbs (asb), being $1 \text{ asb} = \pi^{-1} \text{ cd m}^{-2}$. Scotopic conditions correspond approximately to $\pi \cdot 10^{-3} \text{ asb}$; mesopic conditions between $\pi \cdot 10^{-3} \text{ asb}$ to $\pi \text{ asb}$, and values greater than $\pi \text{ asb}$ correspond to photopic conditions. Adapted from Cabello⁵ and Otero et al.⁶

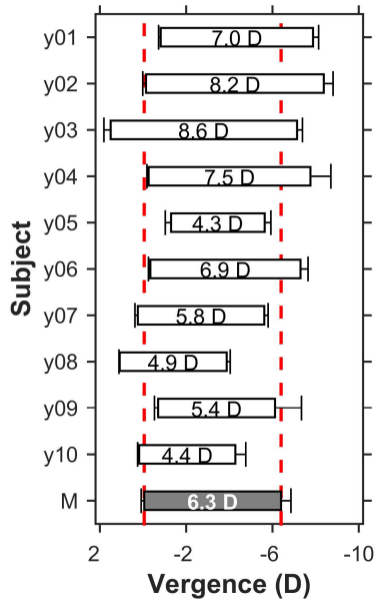
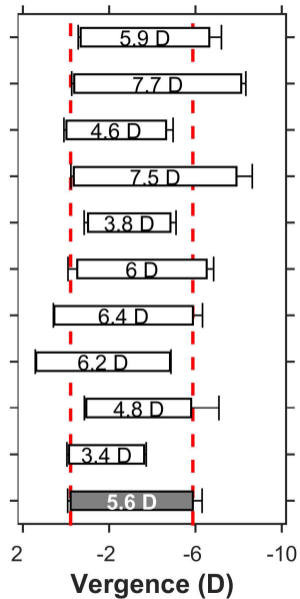
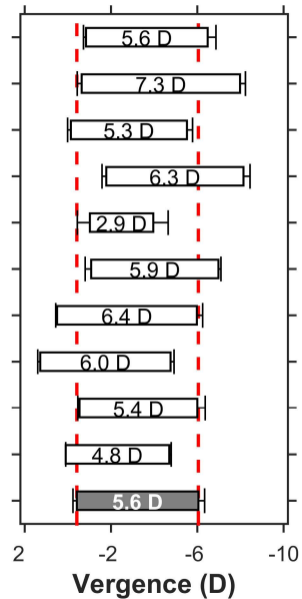
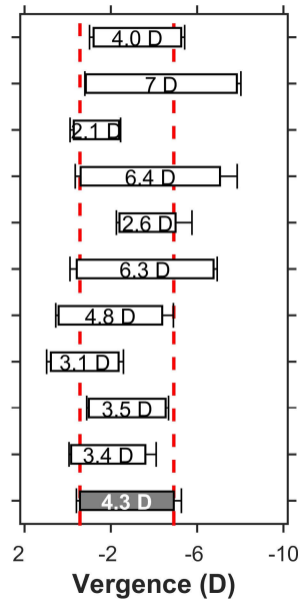
Figure 2. Amplitude of accommodation for the young subjects for each retinal illuminance. Subjects are ranked by age with younger on top. The width of the bars indicates the amplitude of accommodation, the left border is the far point and the right border of the bar is the near point of each subject. Red vertical dashed lines show the mean far point and near point among all the young subjects. The left error bars represent the 1.96 SEM of the far point, whereas right error bars represent the 1.96 SEM of the near point. The label M (filled bars) stands for the mean among subjects.

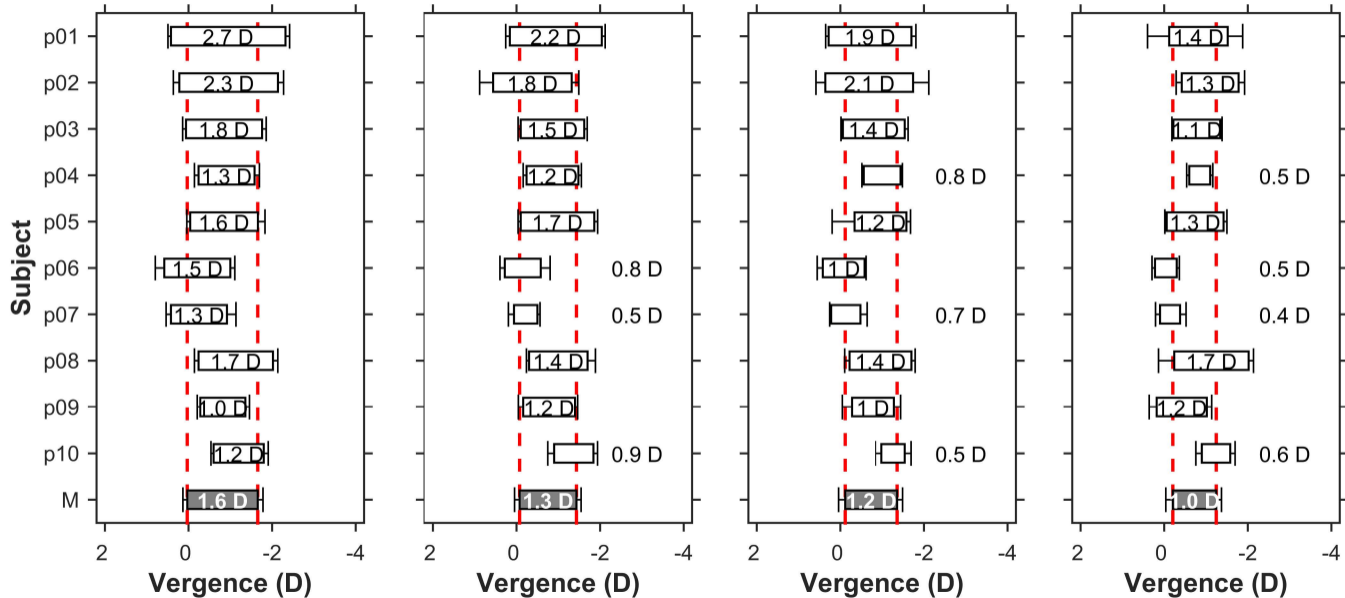
Figure 3. Amplitude of accommodation for the presbyopic subjects for each retinal illuminance. Other details as in Figure 2.

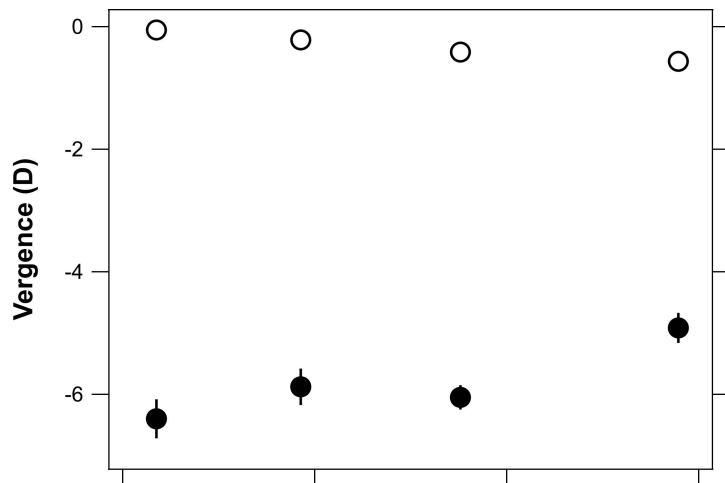
Figure 4. Far point (solid circles) and the near point (empty circles) under different target luminance levels, for young subjects (top left panel) and for presbyopes (top right panel). Bottom panels show the relationship between the logarithm of the luminance and the amplitude of accommodation for young subjects (bottom left panel) and for presbyopes (bottom right panel). The values on the top x-axis in the upper panels are the retinal illuminance (in Trolands) corresponding to each log luminance level on the bottom x-axis. They were added to allow for direct comparisons with Figures 2 and 3. The length of the error bars represents the Gaussian estimate of the 95% confidence

intervals (± 1.96 SEM) around the mean values. Note that in many cases the error bars are so small in length that they are occluded by the symbols themselves.



5074 Td**2138 Td****821 Td****222 Td**

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Young Group**Presbyope Group**