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ORIGINAL ARTICLE

Comparison of Letter and Vernier Acuities with Dioptric and Diffusive Blur

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ABSTRACT: We assessed the influence of dioptric and diffusive blur on normal subjects' letter and Vernier acuity in two experiments. In the first experiment, letter acuity was measured for isolated black Sloan letters and Vernier acuity was determined for a pair of black vertical abutting or nonabutting lines. Targets were viewed through plus lenses that produced 0, 1, 2, 4, and 8 D of dioptric blur. In the second experiment, letter acuity was determined for bright 4-position Ts and Vernier acuity was measured for a pair of bright abutting vertical lines. Six levels of imposed diffusive blur were produced by varying the distance between a ground glass screen and the oscilloscope on which the targets were presented. The results of both experiments indicate that letter and Vernier acuity for abutting or closely separated lines worsen in parallel curvilinear fashion, as long as the lines comprising the Vernier targets remain equally detectable when various amounts of dioptric and diffusive blur are imposed. We conclude that both dioptric and diffusive blur introduce common processing limitations for letter and Vernier acuity. (Optom Vis Sci 1999;76:115–120)

Key Words: blur, visual acuity, Vernier acuity

Diffusive and dioptric, lens-induced blur are common clinical entities that occur, for example, in patients with cataracts and uncorrected refractive errors. Although diffusive blur reduces acuity comparably for letter and grating targets,[1] dioptric blur degrades acuity for letters substantially more than for gratings.[2] Presumably, the differential influence of dioptric blur on letter and grating targets is attributable primarily to spurious resolution.[1–3] Nevertheless, this observation raises the possibility that different forms of acuity are unequally affected by blur.

Under optimal conditions, the values of visual acuity achieved for letter and grating targets are similar.[1, 4] Acuity for Vernier offset is substantially better, such that Vernier and other target configurations that produce extremely fine spatial thresholds have been designated as hyperacuity tasks.[5] The effect of blur, and particularly dioptric blur, on fine spatial thresholds such as Vernier acuity is not well established. In this study, we assessed the influence of both dioptric and diffusive blur on Vernier acuity and, for comparison, the effects on letter acuity in the same observers.

METHODS

The effect of dioptric and diffusive blur on acuity for single letter and Vernier targets was compared in two experiments.

Experiment 1

Letter acuity was measured in three observers with corrected-to-normal vision using individual black Sloan letters.[6] Vernier acuity was determined for a target consisting of two black vertical lines. Except for a control experiment, the line dimensions were 1 × 5 times the stroke width of the threshold-acuity letter at each value of imposed dioptric blur (0, 1, 2, 4, and 8 D). We assume that, by scaling the dimensions of the lines to the observers' average letter acuity, the visibility of the Vernier targets remained approximately the same, regardless of blur. Vernier acuity was measured for: (1) abutting lines, (2) lines separated by a gap equal to 0.5 x line length, and (3) lines separated by a constant gap of 10 arc-min. A gap of 0.5 x line length was the largest that could be comfortably presented on our computer monitor in the 8 D-blur condition, at a viewing distance of 2 m. Similarly, a 10 arc-min gap was the largest that could be presented on the monitor in the 1 D-blur condition, at a viewing distance of 11.2 m. Table 1 lists the dimensions of the Vernier lines used for each value of blur. An example of each of the different target configurations for experiment 1 is shown in Fig. 1A–D.

To evaluate the influence of blur-induced changes in visibility on Vernier acuity, we conducted a control experiment in which target size *was* not scaled in proportion to the letter acuity. This

TABLE 1.

Line and gap sizes of Vernier targets in experiment 1 for different amounts of dioptric blur.

Blur (D)	Length and Width of Vernier Lines (arc-min)	0.5 × Line-Length Gap (arc-min)
0	4.12′ × 0.78′	2.06′
1	9.25′ × 1.77′	4.63′
2	20.7′ × 3.95′	10.35′
4	50.27′ × 9.6′	25.14′
8	112.32′ × 21.45′	61.16′

control experiment compared abutting Vernier acuity with 2, 4, and 8 D of imposed dioptric blur for targets of constant size (50.27′ by 9.6′) and for targets that were scaled to the letter-acuity threshold.

All targets had a Weber contrast of −82%, as displayed on a Macintosh computer monitor with a background luminance of 60 cd/m^2. Viewing was monocular, from distances that ranged from 2 to 11.2 m, depending on the amount of imposed blur. Blur was produced by positive trial lenses, superimposed over each observer's optimal distance spectacle correction:

TN RE: −0.50 sphere
SP RE: −2.00 −1.00 × 045
HB LE: −2.50 sphere

The observers' pupil sizes were between 3 and 4 mm, under the conditions of the experiment.

The method of constant stimuli was used to present letters of five different sizes, or Vernier targets with nine different (four right, four left, and one zero offset) horizontal offsets. Stimulus duration was 2 sec. The subjects' task was to identify each letter or to discriminate the direction of Vernier offset, guessing if necessary. The letter acuity threshold was the size of the stroke width for the letter corresponding to the 50% point on the cumulative Gaussian function, fit to the psychometric data. The Vernier threshold was the change in Vernier offset that produced a 1 SD increase in the probability of either "left" or "right" responses, i.e., from 50% to 84% on the fitted psychometric function. Plotted data include the average of at least two replications for each observer.

Experiment 2

Letter and Vernier acuities were determined with and without diffusive blur in three observers with normal or corrected-to-normal vision. One observer, TN, also participated in experiment 1. Refractive corrections for the other two observers were:

KN RE: plano
SC RE: −8.50 sphere (soft contact lens)

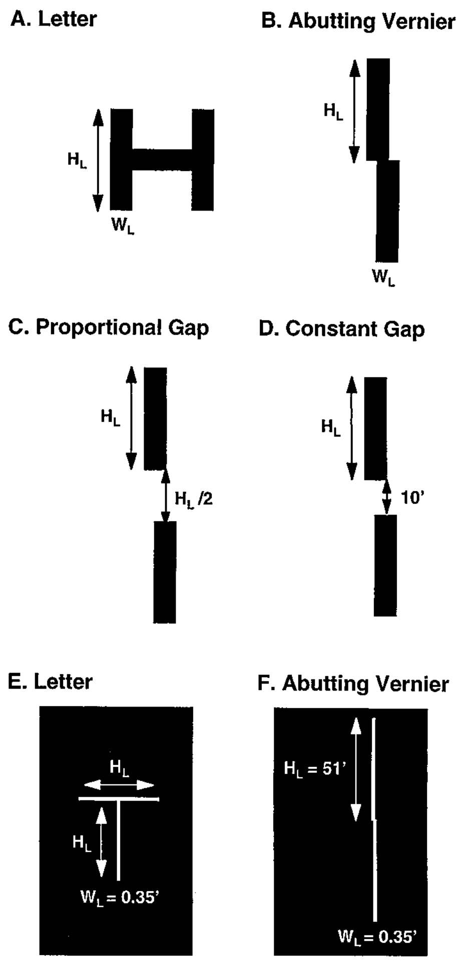

FIGURE 1.

The stimulus configurations are shown for experiments 1 (A–D) and 2 (E–F).

Letter acuity was measured using single, four-orientation letter "Ts," composed of two bright, thin lines of identical length. The task of the observer was to discriminate the orientation of the T. Vernier acuity was determined for a pair of thin, bright, vertical abutting lines. The width of the lines comprising both the letter and Vernier stimuli corresponded to a visual angle of 0.35 arc-min. Fig. 1E–F show examples of the unblurred letter and Vernier stimuli used in this experiment. To compensate for the reduction in stimulus contrast produced by the imposed diffusive blur, all stimuli were presented at a contrast equal to 20 times the detection threshold for a single 0.35 arc-min x 51 arc-min line, identical to one of the two lines comprising the Vernier stimulus. Contrast was controlled by varying the z axis input to a Tektronix 608 oscilloscope, on which the stimuli were displayed. Stimulus generation and response tabulation were under the control of a PC computer. Testing was performed monocularly with the natural pupils at a distance of 3 m, with the stimuli optically superimposed on a uniform background luminance of 50 cd/m^2.

Diffusive blur was produced by a ground glass screen in front of the oscilloscope.[7, 8] Specific details of generating and calibrating various levels of diffusive blur are given elsewhere.[9] In brief, placing the glass screen 0, 1, 3.5, 5, and 7.5 cm in front of the oscilloscope produced five levels of diffusive blur, corresponding to cutoff spatial-frequencies of 17.1, 8.2, 3.35, 2.78, and 1.67 c/deg. The cutoff spatial-frequency of the blurred images is specified as the spatial frequency at which the amplitude of the modulation transfer function drops to 1/e of the maximum value.[8, 10]

Stimuli were presented for a duration of 150 msec. As in experiment 1, the method of constant stimuli was used to determine letter and Vernier acuity thresholds. For letter acuity, six different sizes of Ts were presented 16 times each (i.e., 4 per orientation) in a block of trials. The order of presentation of each letter size and orientation was randomized. For Vernier acuity, 7 horizontal offsets between the upper and lower lines (3 right and 3 left) were each presented 10 times in random order in a block of trials. Because the letter targets in this experiment were not of standard clinical proportions,[11, 12] the acuity threshold was defined as the size of the whole letter that yields 50% correct discrimination on the cumulative Gaussian function, fit to the psychometric data. As in experiment 1, the Vernier threshold was defined as the change in Vernier offset that produces a 1 SD increase in the probability of "left" or "right" responses. Each plotted datum incorporates the average of four to six independent estimates of the threshold for each observer.

The protocols for both experiments were reviewed by the University of Houston Committee for the Protection of Human Subjects, and informed consent was obtained from all observers prior to their participation.

RESULTS

Experiment 1

Average thresholds (±1 SE) for letter and Vernier acuity with various amounts of imposed dioptric blur are shown in Fig. 2. Clearly, acuity thresholds vary with blur and according to the type of target used: letter vs. Vernier. Nevertheless, the thresholds for all four target configurations worsen in a nearly parallel curvilinear fashion with increasing blur, as shown in a repeated-measures analysis of variance by the lack of a significant blur x target-type interaction ($F_{12, 24} = 3.35$, $p = 0.152$). Compared to the unblurred condition, letter acuity worsens by about 1.4 log units (from approximately 20/16 to 20/400) and Vernier acuity for abutting lines worsens by about 1.2 log units (from approximately 16 to 250 arc-sec) when 8 D of dioptric blur is introduced.

For the two smallest amounts of blur, Vernier acuity is poorer for lines separated by 10 arc-min than for either abutting lines or lines separated by 0.5 x line length. These differences in threshold are statistically significant for the no-blur condition ($F_{1, 24} = 11.28$, $p = 0.041$), but not for the 1 D-blur condition $F_{1, 24} = 5.66$, $p = 0.070$).

As shown in Fig. 3, the degradation of Vernier acuity by dioptric blur is more pronounced for targets of constant size than when the dimensions of the Vernier lines are scaled according to the observers' letter acuity. We attribute the significantly more rapid change of Vernier acuity for a target of constant size ($t_4 = 3.49$, $p = 0.025$) to blur-induced changes in the visibility of the target lines, as Vernier acuity for abutting targets is strongly influenced by stimulus visibility.[13, 14]

Experiment 2

Average letter and Vernier acuities (±1 SE) worsen nearly in parallel as the amount of diffusive blur is increased (Fig. 4). In Fig. 4, diffusive blur is expressed in terms of the retinal cut-off spatial frequency of the blurred targets, estimated by multiplying the modulation transfer function (MTF) for each blurred stimulus by the MTF of a well-corrected human eye with a 3.5-mm pupil.[15] Further details of the procedure used to estimate retinal cut-off frequencies are provided in Appendix A. When plotted in the same format, the measures of Vernier acuity vs. diffusive blur reported for abutting lines by Stigmar[16] and Williams et al.[7] are similar to the Vernier data shown in Fig. 4.

For comparison, we replotted the letter and abutting Vernier acuity thresholds from experiment 1 against the estimated retinal

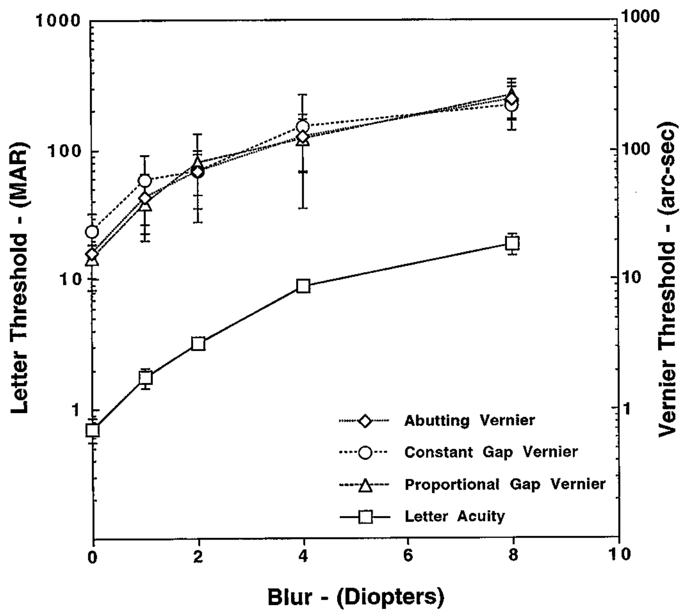

FIGURE 2.

Average letter acuity [minimum angle of resolution (MAR), left axis] and Vernier acuity (in arc-sec, right axis) are plotted vs. dioptric blur, in diopters. The numerical values on the left axis apply also to the right axis. In this and all subsequent figures the error bars are ±1 SE.

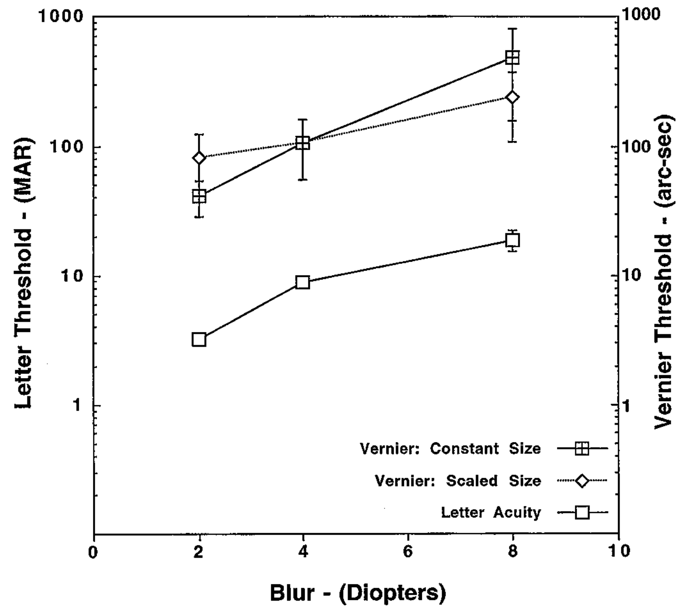

FIGURE 3.

Average acuity, in arc-sec (right axis), is compared for scaled and unscaled abutting Vernier targets with 2 to 8 D of dioptric blur. For comparison, average letter acuity, as MAR (left axis), is reproduced for 2 to 8 D of blur from figure 2.

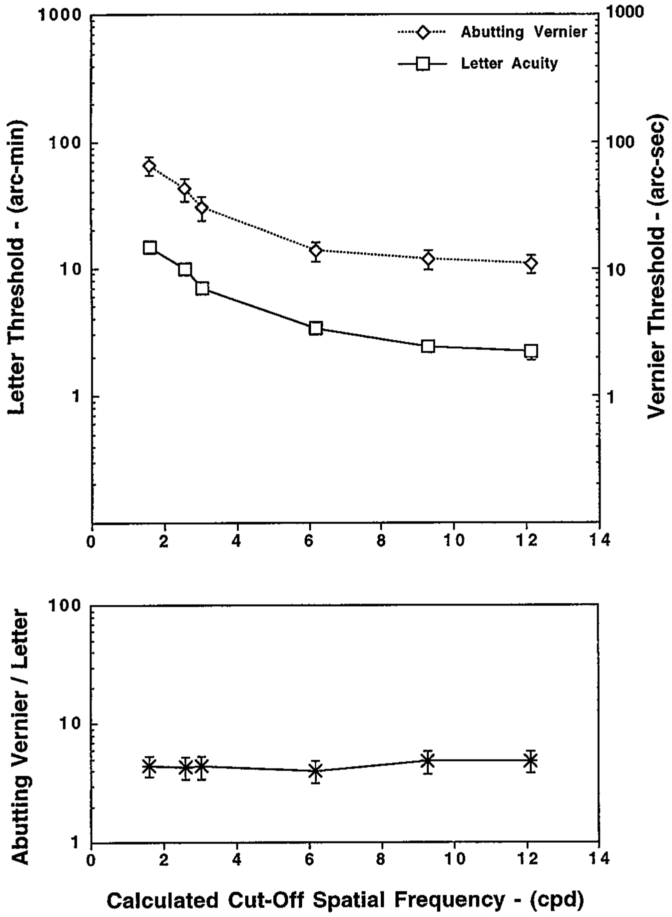

FIGURE 4.

Top: average letter acuity (in arc-min, left axis) and Vernier acuity (in arc-sec, right axis) are plotted against the calculated retinal cut-off spatial frequency of diffusive blur. In this figure, letter acuity is expressed as the entire letter size at threshold. Bottom: the ratio of Vernier to letter acuity is shown as a function of the calculated retinal cut-off spatial frequency of diffusive blur.

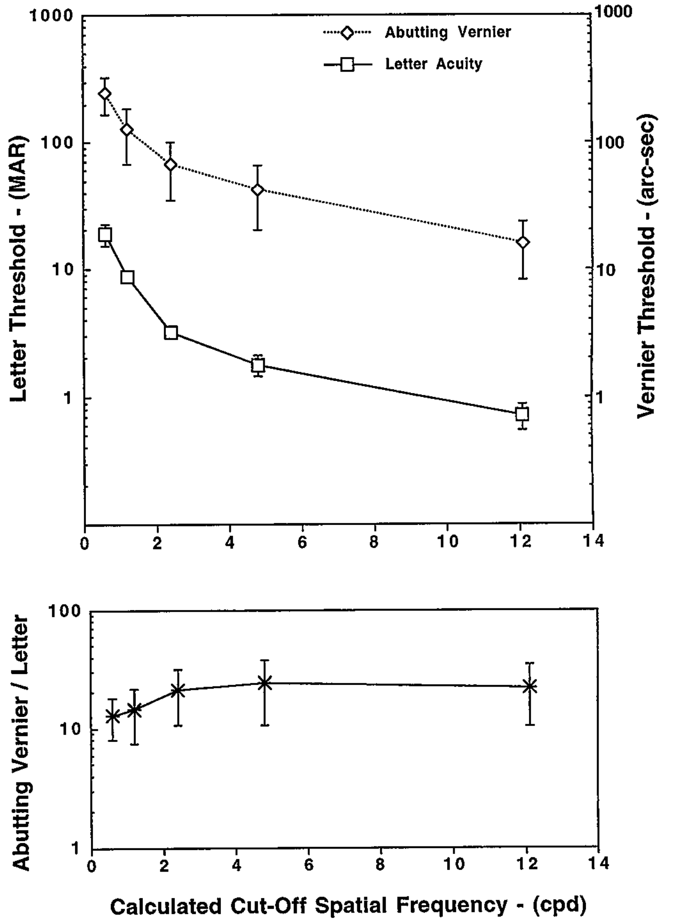

FIGURE 5.

Top: average letter (left axis) and Vernier (right axis) acuities are replotted from Fig. 2 vs. the calculated retinal cut-off spatial frequency of dioptric blur. Bottom: the ratio of Vernier to letter acuity is shown as a function of the calculated retinal cut-off spatial frequency of dioptric blur.

cut-off spatial frequency produced by different amounts of dioptric blur in Fig. 5. Retinal cut-off spatial frequencies for different amounts of dioptric blur were estimated using the formula of Smith[3] and, again, assuming a 3.5-mm pupil (see Appendix B). The similar effects of diffusive and dioptric blur on letter and Vernier acuity are illustrated by the essentially flat difference functions, shown in the bottom panels of Figs. 4 and 5.

DISCUSSION

Our data indicate that letter acuity and Vernier acuity for abutting or closely spaced lines change similarly with the highest spatial frequency that is available in the retinal stimulus. An important aspect of experiment 1 is that we scaled the dimensions of the Vernier lines to maintain approximately equal visibility for each amount of imposed dioptric blur. Similarly, in experiment 2, we set all letter and Vernier stimuli to 20 times the contrast-detection threshold. Because abutting Vernier thresholds depend strongly on target visibility,[13, 14] changes in letter and Vernier acuity with dioptric blur would be unlikely to remain parallel if the dimensions of the Vernier targets were fixed in size (see Fig. 3). Similarly, changes in letter and Vernier acuity with diffusive blur might not remain parallel if the contrast of the targets were not compensated for the luminance attenuation produced by the diffusing screen to maintain constant visibility.

Another important aspect of our experiments is that the principal comparison is between acuity for letters and abutting Vernier stimuli. From results reported by Stigmar[16] and Williams et al.,[7] it is clear that the changes in letter and Vernier acuity with diffusive blur would *not* be parallel if the lines comprising the Vernier target were separated by more than a few arc-min. Stigmar[16] found that Vernier thresholds increase systematically with blur for an abutting-line stimulus, but are essentially unaffected by blur (to a minimum cut-off spatial frequency of approximately 4 cpd) if the lines are separated by a 7 arc-min gap. The data of Williams et al.[7] also indicate that blur exerts a progressively smaller effect on Vernier thresholds as the gap between the Vernier stimuli increases. Consistent with both of these reports, the data from our experiment 1 show that Vernier thresholds differ for abutting and nonabutting stimuli in the absence of blur, but become similar when blur is present (see Fig. 2). Possibly, the differential influence of blur on abutting and separated Vernier stimuli reflects the operation of different visual mechanisms in mediating thresholds for these two types of Vernier configuration.[17]

Indeed, despite the similar dependence of letter and abutting Vernier acuity on dioptric and diffusive blur, it is unwarranted to conclude that the same set of neural mechanisms mediates performance on both of these acuity tasks. In contrast to the results obtained here, letter and Vernier acuities fall off at different rates with retinal eccentricity[1, 18] and with the velocity of image motion, even when equally visible abutting targets are used.[9] Notwithstanding the possibility that nonidentical neural mechanisms underlie letter and Vernier acuity, image blur appears to introduce a common processing limitation for both types of acuity.

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APPENDIX A
Transformation of Diffusive Blur to Retinal Blur

For each distance between the bright target and ground glass screen, an empirical line spread function was determined and converted to a modulation transfer function (MTF) by Fourier transformation. Each empirical MTF was fit with a Gaussian function, which specifies the diffusive blur of the distal stimulus. Stimulus blur was converted to blur at the retina by multiplying the fitted Gaussian function by the MTF of an average human eye with a 3.5-mm pupil. The resultant MTF (*RMTF*) is given by: $RMTF = EMTF * DMTF$ where, *EMTF* is the MTF of the human eye and *DMTF* is the Gaussian function that best fits the MTF of the oscilloscope-ground-glass-screen combination.

The *EMTF* was estimated using the two parameter equation suggested by Johnson[19] and later verified by Jennings and Charman:[15]

$$EMTF = e^{\left(\frac{f}{f_c}\right)^n}$$

where, f_c is a constant frequency and n is the index of the MTF.

For pupil diameters between 2.5 and 6 mm, the MTF index n and the constant frequency f_c were approximated by linear functions of pupil size. The equations for n and f_c are given below: $n = -0.057p + 1.2$ and $f_c = 2.14p + 20$ where, p is the pupil diameter in mm. The above equations were obtained using data reported by Campbell and Gubisch,[20] and included in the paper by Jennings and Charman.[15]

The spatial frequency that corresponds to a 37% level of modulation in the *RMTF* was defined as the retinal cut-off spatial frequency.

APPENDIX B
Transformation of Dioptric Blur to Retinal Blur

Dioptric blur was converted to retinal blur using the method described by Smith.[3] The MTF of a lens (LMTF) is modeled using the equation:

$$LMTF = \frac{2J_1(x)}{x}$$

where $J_1(x)$ is the first-order Bessel function and x is its argument. Because this equation cannot be evaluated at $x = 0$, an equivalent equation, given below, was used.

$$LMTF = J_0(x) + J_2(x)$$

where, $J_0(x)$ and $J_2(x)$ are 0th and 2nd order Bessel functions, respectively.

First, to determine the spatial frequency that corresponds to a criterion level of modulation(37% in our case), the argument of the Bessel function x was determined iteratively. Next, the retinal cut-off frequency (RCF) was determined using the following equation:

$$RCF = RL * L0$$

where, RL is the linear retinal cut-off frequency and L0 is the distance of the pupil from the retina in m. The value of L0 used in our calculations was 0.0204 m.[21] The equation for RL is:

$$RL = \frac{x}{\pi p D}$$

where, p is the pupil diameter in m and D is the amount of lens-induced defocus in diopters.

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