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THE EFFECT OF PUPIL SIZE AND WAVEFRONT ABERRATION OF THE EYE ON BINOCULAR SUMMATION

Takushi Kawamorita*, Nobuyuki Shoji*
*Department of Orthoptics and Visual Science, Kitasato University School of Allied Health Sciences, Sagamihara, Japan.

Abstract
We investigated the effect of natural pupil and wavefront aberration of the eye on the binocular summation. Nine volunteers took part in this study. Continuous recording of natural pupil diameters under monocular and binocular conditions was performed during each examination; contrast sensitivity, both distant and near visual acuity, and refraction. The pupil diameters were measured with an infrared pupillometer FP-10000 (TMI). Aberrometry measurements were performed with ARK-10000 (Nidek). Zernike coefficients were recalculated for the pupil diameters under the monocular and binocular conditions with Schwiegerling's method of recalculating the expansion coefficient. Significant differences were found between the monocular and the binocular contrast sensitivity at the spatial frequencies greater than or equal to 6 c/deg ($p < 0.05$). The binocular summation ratio significantly heightened with the increase of the spatial frequencies ($p < 0.05$). The monocular visual acuity, both distant and near, was significantly worse than the binocular acuity ($p < 0.01$). Mean pupil diameters examined under the monocular condition significantly increased as compared to the binocular condition ($p < 0.0001$). With the increases in the pupil diameters, the optical aberrations significantly increased ($p < 0.05$). These results suggest that the effect of pupil size emphasizes binocular summation.

Keywords: pupils, binocular vision, ocular aberrations, contrast sensitivity, visual acuity.

Introduction
Binocular vision is known to be superior to monocular vision in all aspects: contrast sensitivity, limit of resolution, visual reaction time and so on.[1-4] This phenomenon of overall superiority is often called binocular summation. Psychophysical studies[1] suggest that the ratio of the binocular to the average of the monocular contrast thresholds for sine-wave gratings is about equal to √2. Binocular summation can be attributed to one or more of various factors, for instance, a probability factor or a neural factor. The former is based on a model predicted by the probability theorem[1, 5]; the latter is based on the activity of single cortical cells in the striate cortex.[6, 7]

Also, there is a similar term referred to as binocular luminance summation, which is defined as the increase in the pupil diameters from the binocular to the monocular viewing condition.[8] That is, at the bare mention of covering one eye, the pupil diameters enlarge. Then, it is not clear how the pupil enlargement affect ocular wavefront aberration or binocular summation. With the increases in the pupil diameters, the optical aberrations increase,[9] making the point and line spread functions (PSF and LSF) spread.[10] Therefore, modulation transfer functions (MTF) and the Strehl ratio decrease to diminish retinal image sharpness objectively.[11, 12] In addition, possible influences are the Stiles-Crawford effect,[13] changes of pupil centration,[14] and retinal illuminance.[15] Consequently, change in pupil diameters can affect subjective visual performances: visual acuity, contrast sensitivity and such.

As just described, it is not only common knowledge but also clearly demonstrable that the pupils have a great deal to do with visual performance. Although the facts exist, so far, few studies have reported on the relationship between binocular summation and binocular luminance summation. [16, 17] The purpose of this study is to show how the activity of the pupils affects binocular summation.

Materials And Methods
Nine healthy volunteers (mean age 21.2, 2 males and 7 females) took part in this study. The tenets of the Declaration of Helsinki were followed in this study. Informed consent was obtained from all volunteers, who were all emmetropic or with slight refractive error. The exclusion criteria included visual acuity (logMAR) at distance of worse than 0 in

monocular vision, a refractive error higher than S ± 1.00 D or C – 1.00 D, and wearing contact lenses or spectacles, this last in order to raise the precision of the laboratory measurements.

Contrast sensitivity was measured at target spatial frequency values of 1.5, 3, 6, 12 and 18 cycles / degree (c/deg) using the vision contrast test system 6500® (Vistech) at distance of 3 m. Binocular summation ratios were calculated by dividing the binocular sensitivity by the monocular sensitivity.

Monocular and binocular recognition visual acuities were measured using the distance logMAR chart LCV - 2® (Neitz, Tokyo, Japan) at a distance of 5 m and the near distance logMAR chart® (Nitten, Nagoya, Japan) at a distance of 50 cm. The latter can measure more particular minimum resolvable distance with low contrast Landolt at 25 and 6 %, not only 100 %. Here contrast is defined as $(L_{max} – L_{min}) / (L_{max} + L_{min}) \times 100$ %, where L_{max} and L_{min} are the maximum and minimum luminances. The endpoint criterion of visual acuity was determined as 3 of 5 letters on a line.

The natural pupil diameters were measured with an infrared electronic pupillometer FP - 10000® (TMI, Saitama, Japan), connected to a laptop PC to be analyzed using the proprietary software (TMI version 1.08). This measuring instrument can measure in open-view and real times during examinations of visual performances.

Aberrometry measurements were performed with OPD - Scan ARK - 10000® (Nidek, Aichi, Japan). This is an optical path difference scanning system-based device. Zernike coefficients were recalculated for pupil diameters under the monocular and binocular conditions, using Schwiegerling's technique for recalculating expansion coefficients for an arbitrary pupil size, based on the expansion of coefficients of the 6.0 mm pupil size.[18] Measurement values were estimated to the nearest 0.01 mm.

Measurements of refractive error in the monocular and binocular conditions were performed with Flexible - Ref FR 5000® (Grand Seiko, Fukuyama, Japan), which is an infrared, open-view, objective hand autorefractor. The refraction was converted into spherical equivalent refraction (D).

The study was carried out as described. Continuous recording of pupil diameters was performed during each examination (i.e. distance and near visual acuity, contrast sensitivity) to calculate the average of horizontal pupil diameters; momentary effects of blinking were disregarded. The recording of pupil diameters in refraction measurements was performed for 10 sec. before and 10 sec. after each refraction measurement. Also, each examination was performed under both the monocular and binocular conditions. Under the monocular condition one eye (the non-dominant eye) was covered with a black patch. All measurements performed under photopic lighting conditions were done with ambient and chart lighting of 85 cd/m^2 and by the same clinical investigators.

Statistical analysis was made with a paired-t test for parallel between monocular and binocular conditions, and with repeated measure analysis of variance (ANOVA) for binocular summation ratios, all with $\alpha = 0.05$.

Results And Discussion

Visual performances and mean pupil diameters during examinations in the monocular and binocular conditions are shown in Table 1. In contrast sensitivity, significant differences were found between the monocular contrast sensitivity and the binocular contrast sensitivity at spatial frequencies greater than or equal to 6 c/deg ($p < 0.01$ for 12 and 18 c/deg, $p < 0.05$ for 6 c/deg) (Figure 1-a). The binocular summation ratio significantly heightened with the increase in the spatial frequencies ($p < 0.05$) (Figure 1-b). Figures 2 and 3 show the cumulative percentage of eyes at each level of logMAR values. The monocular logMAR values for distance were significantly worse than the binocular logMAR ($p < 0.01$) (Table 1, Figure 2). Much the same was true of logMAR for near vision ($p < 0.01$) (Table 1, Figure 3). Also, as contrast of Landolt-C decreased, monocular logMAR values were disposed to decrease at a greater rate than binocular logMAR values (Figure 4). Mean pupil diameters across the board under examinations of the monocular condition significantly increased as compared to the binocular condition ($p < 0.0001$). As shown in Table 2, all the parameters of higher order aberrations—total higher order, comma-like (S3+S5), spherical-like (S4+S6), S3, and S4—significantly increased. However, in spherical equivalent refraction a significant difference was not found between the monocular and binocular conditions ($p > 0.05$).

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Table 1. Mean pupil diameter and visual performance (Contrast sensitivity, logMAR, S.E.) under monocular and binocular vision. SF, spatial frequency; C, contrast

Measurement			Binocular			Monocular			P Value
Contrast Sensitivity	pupil (mm)		3.16	±	0.48	4.16	±	0.74	< 0.0001
	SF	1.5 c/deg	1.77	±	0.16	1.74	±	0.17	N.S.
		3 c/deg	2.14	±	0.15	2.06	±	0.18	N.S.
		6 c/deg	2.30	±	0.12	2.20	±	0.17	< 0.05
		12 c/deg	2.15	±	0.10	2.01	±	0.20	< 0.01
		18 c/deg	1.77	±	0.15	1.61	±	0.22	< 0.01
logMAR at distance	pupil (mm)		3.24	±	0.62	4.09	±	0.66	< 0.0001
	value		-0.17	±	0.09	-0.05	±	0.10	< 0.01
logMAR at near	pupil (mm)		3.09	±	0.52	4.02	±	0.83	< 0.0001
	C	100%	-0.14	±	0.06	-0.09	±	0.06	< 0.01
		25%	-0.03	±	0.10	0.04	±	0.11	< 0.01
		6%	0.22	±	0.10	0.31	±	0.12	< 0.01
S.E. (D)	pupil (mm)		3.23	±	0.61	4.19	±	0.58	< 0.0001
	value		0.16	±	0.40	0.11	±	0.35	N.S.

Table2. Mean pupil diameter and higher order aberration under monocular and binocular vision. Data are expressed as mean ± SD. S.E., spherical equivalent refraction; RMS, root mean square

Measurement			Binocular			Monocular			P Value
Contrast Sensitivity	pupil (mm)		3.16	±	0.48	4.16	±	0.74	< 0.0001
	wave aberration RMS (μm)	Total	0.036	±	0.021	0.079	±	0.066	< 0.01
		S3+S5	0.033	±	0.020	0.064	±	0.043	< 0.001
		S4+S6	0.011	±	0.011	0.038	±	0.058	< 0.05
		S3	0.033	±	0.020	0.062	±	0.041	< 0.001
		S4	0.011	±	0.011	0.038	±	0.057	< 0.05

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Table2. Continuation

Measurement			Binocular			Monocular			P Value
logMAR at distance	pupil (mm)		3.24	±	0.62	4.09	±	0.66	< 0.0001
	wave aberration RMS (μm)	Total	0.039	±	0.025	0.071	±	0.041	< 0.0001
		S3+S5	0.036	±	0.025	0.060	±	0.036	< 0.01
		S4+S6	0.012	±	0.009	0.031	±	0.031	< 0.01
		S3	0.036	±	0.025	0.059	±	0.035	< 0.0001
		S4	0.012	±	0.009	0.030	±	0.031	< 0.01
logMAR at near	pupil (mm)		3.09	±	0.52	4.02	±	0.83	< 0.0001
	wave aberration RMS (μm)	Total	0.034	±	0.020	0.073	±	0.057	< 0.05
		S3+S5	0.032	±	0.020	0.060	±	0.039	< 0.001
		S4+S6	0.010	±	0.009	0.034	±	0.048	< 0.05
		S3	0.031	±	0.020	0.058	±	0.038	< 0.001
		S4	0.010	±	0.009	0.034	±	0.048	< 0.05
S.E. (D)	pupil (mm)		3.23	±	0.61	4.19	±	0.58	< 0.0001
	wave aberration RMS (μm)	Total	0.039	±	0.025	0.076	±	0.047	< 0.01
		S3+S5	0.036	±	0.026	0.063	±	0.038	< 0.01
		S4+S6	0.012	±	0.009	0.034	±	0.038	< 0.01
		S3	0.036	±	0.025	0.062	±	0.037	< 0.001
		S4	0.012	±	0.009	0.033	±	0.038	< 0.05

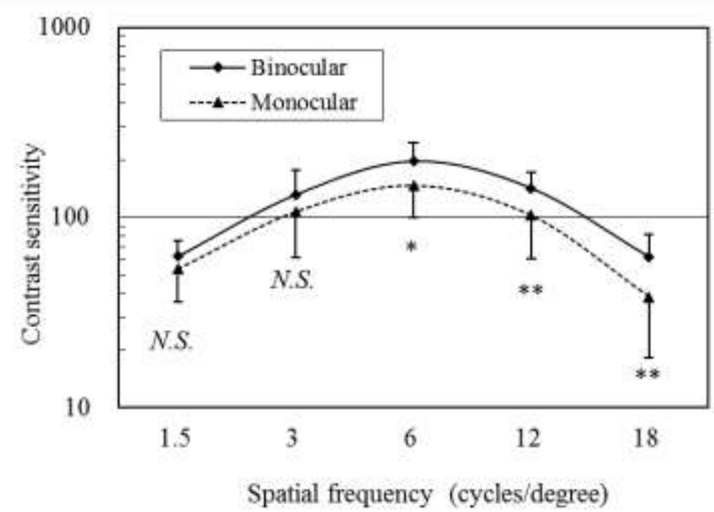

*Figure 1-a. Contrast sensitivity under monocular and binocular vision. Data are expressed as mean ± SD. Statistical significance: 6 c/deg, *P < 0.05, 12 and 18 c/deg, **P < 0.01; paired t test.*

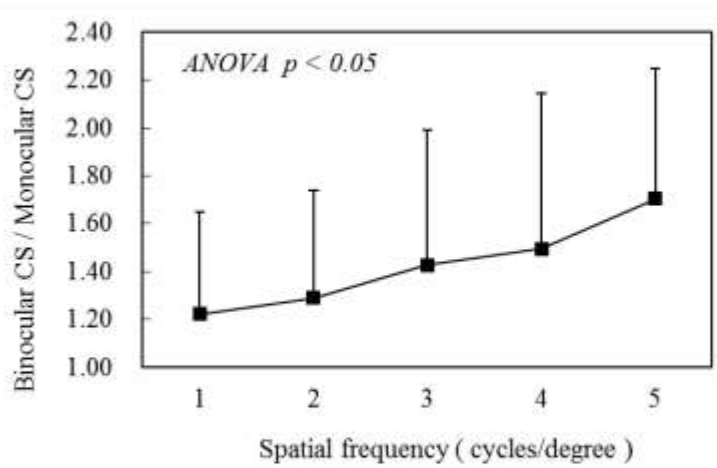

Figure 1-b. The relationship between binocular summation ratio and spatial frequency. Heavy line shows √2 times value. Statistical significance: P < 0.05; repeated measure analysis of variance (ANOVA).

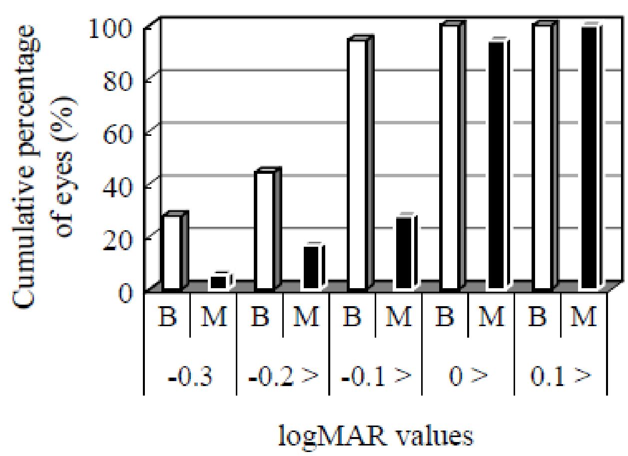

Figure 2. Comparison of monocular and binocular cumulative percentages at each level of far distant logMAR values. B, binocular vision; M, monocular vision

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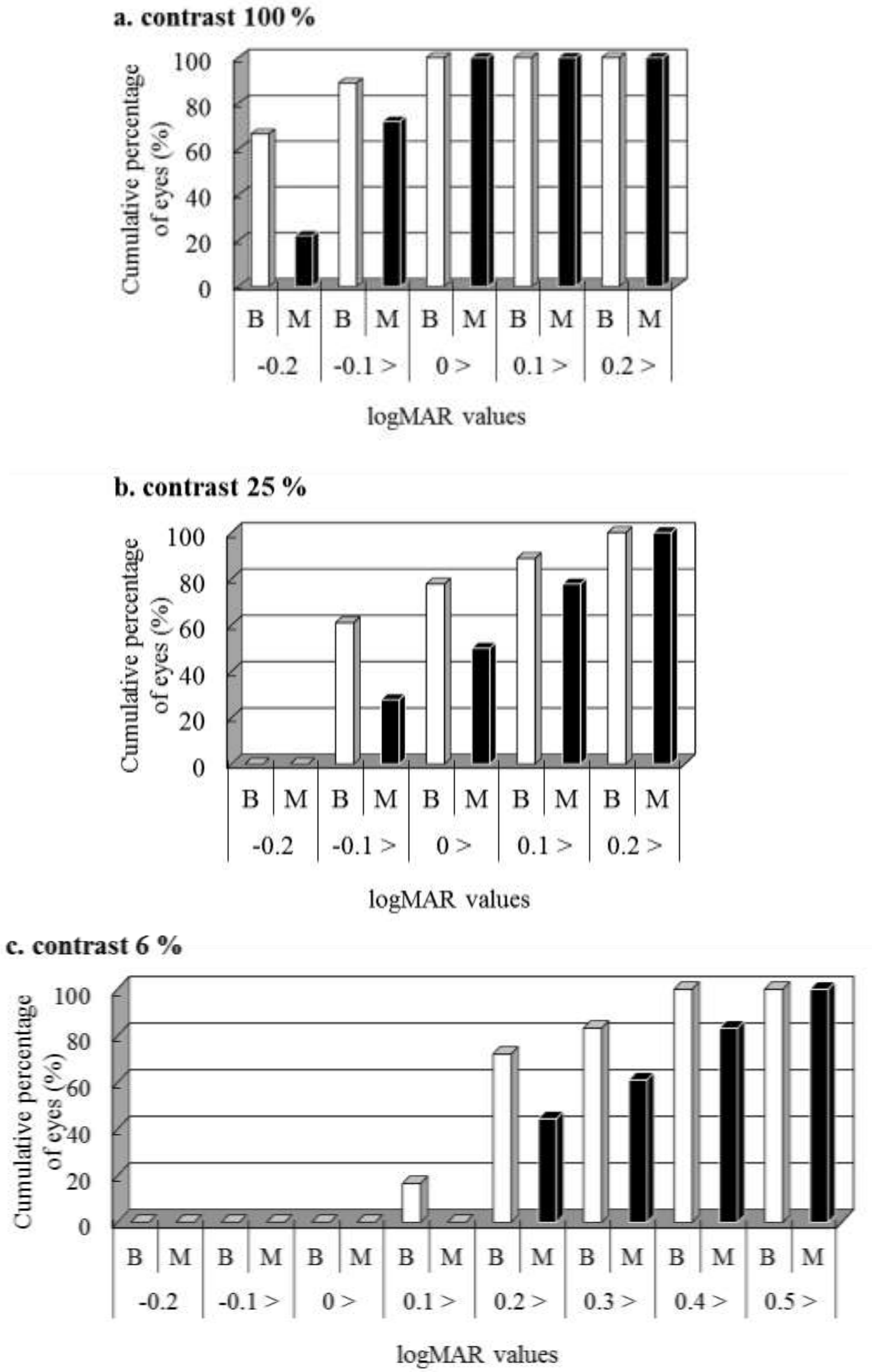

Figure 3. Comparison of monocular and binocular cumulative percentages at each level of near distant logMAR values for three levels of contrast (a, 100 %; b, 25 %; c, 6 %). B, binocular vision; M, monocular vision

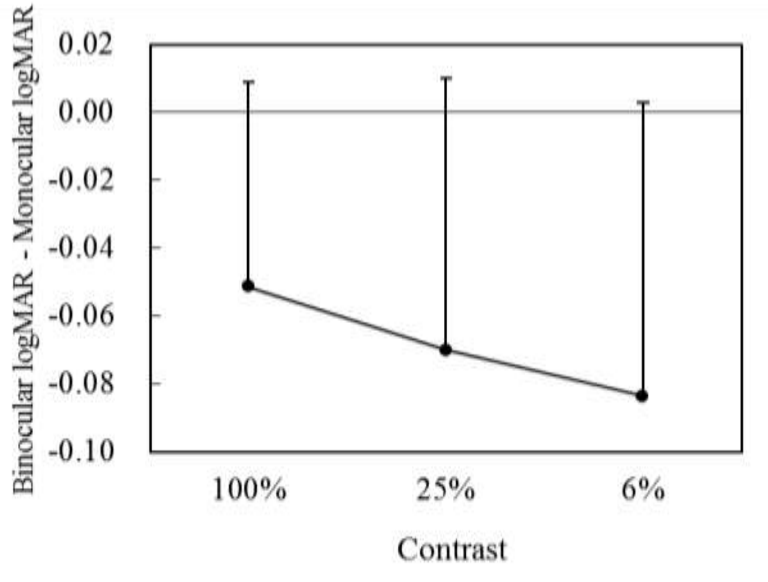

Figure 4. The relationship between contrast of Landolt C and the differences defined as binocular logMAR - monocular logMAR at near distance. Data are expressed as mean ± SD. Statistical significance: N.S.; repeated measure analysis of variance (ANOVA).

In contrast sensitivity, although there were no differences between monocular and binocular conditions at low spatial frequencies (1.5 and 3 c/deg), monocular contrast sensitivity at high and middle spatial frequencies (from 6 to 18 c/deg) significantly decreased as compared to binocular vision, and the binocular summation ratio significantly rose with the increase of spatial frequencies. These results in Figure 1 are approximately congruent with those reported by Campbell and Green[1] in that the ratio of the binocular to the average of the monocular thresholds was approximately equal to √2. However, our results are not in line with their results in that our binocular summation ratio significantly rose with the increase in spatial frequencies. The difference would be attributed to the reason that we did not used atropine and artificial pupil in both eyes to investigative effects of natural pupil and accommodation.

In visual acuity, both distance and near vision binocular superiority were found. Because it is measured in terms of the smallest identifiable high-contrast target and because small sizes correspond to high spatial frequencies, visual acuity measures visual sensitivity largely in the higher frequency regions of the contrast sensitivity function. [19] The results, therefore, fit in with those of contrast sensitivity at high spatial frequencies. Also, Home[20] showed that as Landolt-C contrast decreased, binocular superiority became greater. In our results, although a significant difference was not found, it demonstrated the same tendency.

Binocular summation has generally been recognized as either a probability summation based on a hypothesis in which the two eyes are independent, or a neural summation based on synaptic convergence of monocular inputs. Pirenne[21] argued that binocular summation could be explained by the probability summation between independent channels. However, Blake and Fox[22] demonstrated that relative superiority of binocular summation is greater than that expected on the model of probability summation and can be influenced by certain variables, such as pupil size and fixation. Our results bear out the importance of pupil size to binocular summation. Actually, Table 1 clearly shows that pupils widely dilated under conditions of monocular vision. Higher order optical aberrations for the pupil sizes under the monocular vision were significantly increased compared with those under the binocular vision. Campbell and Gubisch[23] calculated the MTF from white light line spread functions. They found that both the contrast reduction due to the optics of the eye and, with increasing pupil size, the performance of the optics deviated progressively from a perfect optical system, all of which was mainly due to the effects of spherical aberration. Losada et al. [24] also argued that at all luminances, the falloff in contrast sensitivity at high frequencies is mainly due to optical factors. These reports support our research findings demonstrating the pupil-size effect on binocular summation. Moreover, spherical equivalent refraction did not significantly range between monocular vision and binocular vision. Therefore, this result shows that fluctuations of the accommodation system with the increase of pupil size do not have a great impact on binocular summation.

Also, although the precise cause of the phenomenon is as yet not well known, the phenomenon is considered to depend on the visual pathways by which signals from the two eyes converge, stereopsis,[25, 26] or to be the simultaneous use of nonoverlapping fields of the two eyes in exotropia, peripheral fusion, the incomplete suppression of the deviated eye.[8] Regardless of what the cause of the binocular luminance summation may be, the results are exemplified by three facts: (1) the pupil is larger when either eye is occluded than when both eyes are illuminated; (2) with the increased pupil size the higher order aberration increases, resulting in reduced retinal image quality, and (3) visual performance in monocular vision is inferior to that in binocular vision.

Conclusion

In conclusion, our results suggest that the enlargement in the pupil diameters from the binocular to the monocular viewing conditions causes an increase in optical aberration, resulting in reduced retinal image quality and the consequent decrease in subjective visual performance. On binocular summation, pupil size produces a functional enhancement effect; it is not a mere artifact. This study provides new and important information on the functional significance of the pupil size on binocular summation.

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