OPO OPHTHALMIC & PHYSIOLOGICAL OPTICS
THE JOURNAL OF THE COLLEGE OF OPTOMETRISTS

Ophthalmic & Physiological Optics ISSN 0275-5408

Through-focus performance with multifocal contact lenses: effect of binocularity, pupil diameter and inherent ocular aberrations

Sotiris Plainis[1,2], George Ntzilepis[1], David A Atchison[3] and W Neil Charman[2]

[1]Institute of Vision & Optics, University of Crete, Heraklion, Crete, Greece, [2]Faculty of Life Sciences, University of Manchester, Manchester, UK, and [3]Institute of Health & Biomedical Innovation and School of Optometry & Vision Science, Queensland University of Technology, Brisbane, Australia

Citation information: Plainis S, Ntzilepis G, Atchison DA & Charman WN. Through-focus performance with multifocal contact lenses: effect of binocularity, pupil diameter and inherent ocular aberrations. *Ophthalmic Physiol Opt* 2013, **33**, 42–50. doi: 10.1111/opo.12004

Keywords: depth-of-focus, multifocal contact lenses, spherical aberration, visual acuity

Correspondence: Sotiris Plainis
E-mail: plainis@med.uoc.gr

Received: 14 August 2012 ; Accepted: 11 October 2012

Abstract

Purpose: To evaluate the effects of the wearer's pupil size and spherical aberration on visual performance with centre-near, aspheric multifocal contact lenses (MFCLs). The advantage of binocular over monocular vision was also investigated.
Methods: Twelve young volunteers, with an average age of 27 ± 5 years, participated in the study. LogMAR Visual Acuity (VA) was measured under cycloplegia for a range of defocus levels (from +3.0 to −3.0 D, in 0.5 D steps) with no correction and with three aspheric MFCLs (Air Optix Aqua Multifocal) with a centre-near design, providing correction for 'Low', 'Med' and 'High' near demands. Measurements were performed for all combinations of the following conditions: (1) artificial pupils of 6 and 3 mm diameter, (2) binocular and monocular (dominant eye) vision. Depth-of-focus (DOF) was calculated from the VA vs defocus curves. Ocular aberrations under cycloplegia were measured using iTrace.
Results: VA at −3.0 D defocus (simulating near performance) was statistically higher for the 3 mm than for the 6 mm pupil ($p = 0.006$), and for binocular rather than for monocular vision ($p < 0.001$). Similarly, DOF was better for the 3 mm pupil ($p = 0.002$) and for binocular viewing conditions ($p < 0.001$). Both VA at −3.0 D defocus and DOF increased as the 'addition' of the MFCL correction increased. Finally, with the centre-near MFCLs a linear correlation was found between VA at −3.0 D defocus and the wearer's ocular spherical aberration ($R^2 = 0.20$ $p < 0.001$ for 6 mm data), with the eyes exhibiting the higher positive spherical aberration experiencing worse VAs. By contrast, no correlation was found between VA and spherical aberration at 0.00 D defocus (distance vision).
Conclusions: Both near VA and depth-of-focus improve with these MFCLs, with the effects being more pronounced for small pupils and for binocular rather than monocular vision. Coupling of the wearer's ocular spherical aberration with the aberration profiles provided by MFCLs affects their functionality.

Introduction

In contrast to most aspects of visual performance, which typically only start to decline after the age of about 50 years, accommodative ability falls almost linearly with age from at least the early teenage years, with presbyopic symptoms starting to occur at the age of 40–45 years. There are several prescriptive and surgical approaches that can potentially satisfy the needs of the presbyope. Although the most common correction is by using additional positive lenses, the majority of other procedures are designed to counteract the effects of reduced amplitude of accommodation in the ageing eye by extending the ocular depth-of-focus (DOF).

Contact lens correction of presbyopia has long been a major challenge, due to the difficulty of producing complex lens designs capable of providing sharp distance and near vision for every visual task. Current prescriptive modalities with soft contact lens include: (1) Single-vision contact lenses for distance correction combined with reading spectacles for near tasks, (2) monovision, with one eye being corrected optimally for distance and the fellow eye for near[1–4], (3) alternating vision (image) correction, and (4) a range of designs (i.e., diffractive, bifocal, varifocal, multifocal) offering simultaneous vision (image) correction.[5–7] Although the contact lens industry has, in recent years, produced a remarkable range of patented contact lens designs, the majority of presbyopic contact lens patients (about 63%) are still fitted with non-presbyopic corrections, with simultaneous image designs representing only 29% of all the fittings.[8]

In simultaneous-image correction, light rays passing through the pupil to form the retinal image encounter either both distance and near corrections (*bifocal, two-foci*) or a smooth transition in power between distance and near corrections (*multifocal, multiple foci*). Thus, any region of the retina receives both in-focus and out-of-focus images. Ideally the brain selects the in-focus stimulus while suppressing out-of-focus stimuli.[9] In practice, the contrast of the desired in-focus image is reduced by the superimposed out-of-focus image(s).[6,10] Multifocal designs involve a progressive, rotationally symmetric, gradation of power from the centre to the edge of the lens optical zone. This is achieved by the use of one or more aspheric surfaces, which produce greater power either in the lens centre (centre-near) or in the periphery (centre-distance).[10–14]

Any variation of zonal power is equivalent to spherical aberration. In effect, multifocality is accomplished in soft aspheric contact lenses by incorporating controlled spherical aberration: negative in centre-near and positive in centre-distance designs. Although the 'best' image on the retina is degraded by the induced spherical aberration, this is outweighed by the increase in the vergence range over which there is no apparent deterioration in retinal image quality, i.e. DOF is increased.[5,12,15–18] However, an intriguing inter-individual variability in subjective tolerance has been observed, which may be attributed to inherent optical factors, such as pupil size,[11,19] higher-order ocular aberrations,[12,20–22] binocular summation[23] and personality characteristics, such as tolerance to blur[24] and anxiety.[25] One higher-order ocular aberration that might be expected to be particularly important in relation to multifocal contact lens (MFCL) performance is spherical aberration since, depending upon its sign, it may enhance or reduce the effects of the lenticular spherical aberration. This study investigates for the first time the combined effects of pupil size, wearer's ocular spherical aberration, and binocularity on through-focus performance with MFCLs.

Methods

Participants

Twelve young volunteers (nine females, three males), with an average age of 27 ± 5 years (range 22–29 years), participated in the study. Exclusion criteria included: spectacle-corrected visual acuity worse than 0.00 logMAR (6/6, 20/20 equivalent) in each eye, hyperopia > 0.75 D, myopia > 6.00 D, astigmatism > 0.50 D, anisometropia > 0.50 D, abnormal phorias and any history of refractive or other ocular surgery. Average spherical equivalent was −2.24 ± 2.12 D (range: +0.75 to −5.25 D). Eight subjects habitually wore contact lenses for myopia. Verbal consent was obtained from all participants after they had received an oral explanation of the nature of the study. The study was conducted in adherence to the tenets of the Declaration of Helsinki and followed a protocol approved by the University of Crete Research Board.

Contact lenses

In the experiments that follow, three types of afocal aspheric MFCLs (Air Optix Aqua Multifocal, http://www.airoptix.com) providing correction for 'Low', 'Med' and 'High' near demands, were used. These lenses produce progressively greater axial power in the lens center (center-near design), offering a pupil-dependent increase in the DOF. Their power profiles are shown in *Figure 1*. Although the Low add lens has a single aspheric profile (dominated by 4th-order spherical aberration of about 0.27 μm for a

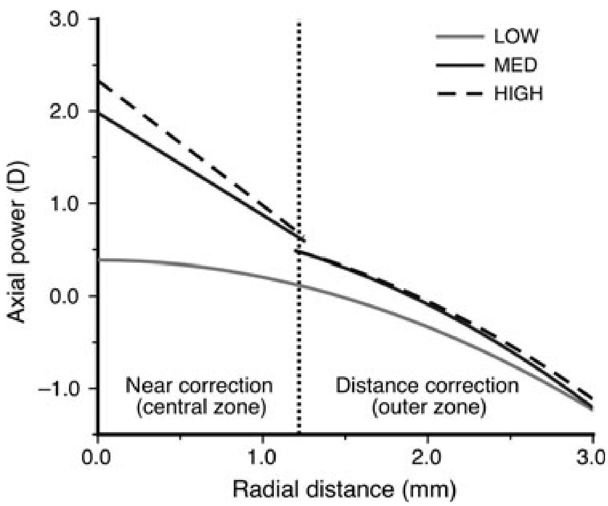

Figure 1. Plots of the axial power as a function of radial distance from the centre of the lens for the three multifocal contact lenses used in this study. Solid lines represent first- and second-order fitted functions (Low add - solid grey line; Medium add – solid dark lines; High add – solid dashed lines). Data are replotted from Vogt *et al.*[26] and Plainis *et al.*[14]

6 mm pupil,[14,26] the profiles of the Med and High adds are more complex, i.e. the central 'add' areas (of diameter ~ 2.6 mm) have different characteristics so that higher-order Zernike spherical aberration terms (i.e., 6th, 8th, 10th) become important.

Experimental Procedure

Visual acuity (VA) was assessed for a range of defocus levels using positive and negative spherically-powered spectacle lenses (from +3.00 to −3.00 D, in 0.50 D steps) inserted in a trial frame at 13 mm vertex distance. Subjects were also best-corrected for distance for any sphero-cylindrical refractive error with additional trial lenses. The range of negative lenses (0 to −3.00 D) was selected to simulate through-focus performance for a range of vergences, from 'far' (0.00 D lens, when the chart was viewed directly at 4 m) to 'near' (−3.00 D lens, the chart appearing to lie at 32 cm distance in front of the eye). The positive lenses were used to explore the changes in VA on the other side of optimal focus, since it could be argued that a better compromise between distance and near vision might be achieved by slightly over-plussing the prescription. Measuring VA through a range of powered lenses creates a performance profile over a range of focal demands. This is equivalent to determining VA over a range of distances, without the issues of resizing the letters and maintaining a constant illumination. No compensation was made for spectacle magnification and effectivity, since their effects were relatively small for the lenses used. In the worst case, the trial-lens corrected subject with the highest level of myopia and an additional −3.00 D lens had a spectacle magnification of about 0.9X, equivalent to an under-estimate of about 0.05 in logMAR: this was partly compensated by the fact that lens effectivity meant that insertion of the −3.00 D lens only caused a change of only about −2.50 D in vergence at the cornea.

All measurements were performed under cycloplegia (one drop of cyclopentolate 1%) in order to dilate the pupil to a diameter larger than 6.0 mm and paralyse accommodation. VA was recorded without any CL correction (i.e. naked cornea plus any required spectacle sphero-cylindrical correction) and with the three afocal (i.e. having nominally zero corrective power for distance vision), centre-near aspheric MFCLs under combinations of the following conditions: i) artificial pupils of 3 mm and 6 mm diameter, placed in the trial frame, and ii) monocular (dominant eye) and binocular vision. The order of pupil aperture (3 vs 6 mm) and viewing condition (monocular vs binocular) was counterbalanced. Contact lenses were inserted 30 min prior to the recordings to allow for lens stabilisation.

Visual acuity (VA) was measured with the European-wide logMAR charts (Precision Vision, http://www.precision-vision.com)[27] at 4.0 m distance. Three versions of chart 1 and chart 2 were used for recording the VA with monocular and binocular viewing, respectively. Chart luminance was about 160 cd m^{-2}. Eye dominance was determined by looking through a central hole in an A4 card, held by the participant in both hands away from the body. During the monocular measurements the non-dominant eye was covered with an eye patch. All subjects were asked to identify each letter one by one in each line and to proceed by row until they could no longer name correctly at least one letter in a line. They were instructed to read slowly and guess the letters when they were unsure. The termination rule for stopping was four or five mistakes on a line.

The monochromatic ocular wavefront aberrations for the naked eyes of each participant were measured under cycloplegia with an iTrace aberrometer (http://www.traceytechnologies.com). The Zernike expansion coefficients (in OSA representation[28]) up to 6th order were scaled to 6 mm pupil diameter. The fourth-order ocular spherical aberration coefficient C_4^0 of the dominant eye was used in data analysis.

Results

Figure 2 presents average through-focus performance (defocus curves) for all testing conditions with the naked eye and the three MFCLs. Average (S.D.) values of VA for each condition are shown in *Table 1*. Optimal VA was achieved close to 0.0 D spectacle-lens power (i.e. at the chart distance of 4 m) for all lenses and for both pupil diameters. VA at low levels of defocus (simulating performance for distance) was always better with the naked eye than with MFCLs, although visual acuity with the MFCLs was always better than 0.0 logMAR (6/6, 20/20 equivalent). At higher levels of negative defocus (simulating performance for intermediate and near distances) visual acuity was better the higher the near correction ('High' > 'Med' > 'Low' > naked eye). Moreover, logMAR acuity was always better with the 3 mm than with the 6 mm pupil, and with binocular rather than with monocular viewing. As might be expected from their add effects, with the MFCLs VA declined more rapidly with positive than with negative defocus.

These impressions were confirmed by a 2 × 2 × 4 (pupil aperture × viewing condition × correction) repeated measures ANOVA. There were significant pupil aperture ($F_{1,6}$ = 117.4, $p < 0.001$) and viewing condition ($F_{1,6}$=40.2, $p = 0.001$) main effects, as well as pupil aperture by viewing condition ($F_{1,6}$=12.0, $p = 0.013$) and viewing condition by correction ($F_{3,18}$=5.3, $p = 0.008$) interactions. The effects of correction showed a non-significant trend ($F_{3,18}$=3.9, $p = 0.09$), while the 3-way interaction was marginally non-significant ($F_{3,18}$=3.0, $p = 0.06$).

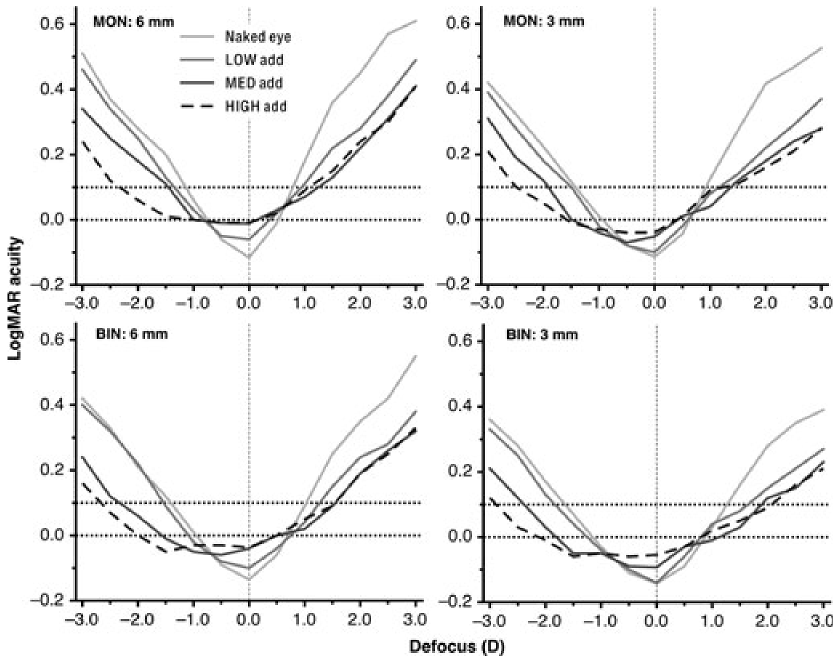

Figure 2. Average plots of visual acuity (logMAR) as a function of defocus (i.e. the power of the spectacle trial lens) for two pupil sizes (3 and 6 mm) and under monocular (dominant eye) and binocular vision for the four types of correction (naked eye, low, medium and high addition multifocal contact lenses). The dotted horizontal lines correspond to the two criteria of acuity (0.0 logMAR - 6/6 Snellen equivalent; 0.1 logMAR - 6/7.5 Snellen equivalent) used for the calculation of depth-of-focus.

The non-significant effects of correction can be explained by the fact that performance for distance is hampered in the use of MFCLs. If a 3-way ANOVA is performed on visual acuity data at −3.0 D defocus, there is a significant correction effect ($F_{3,33}$=16.8, $p < 0.001$), and performance is better with a 3 mm than with a 6 mm pupil aperture ($p = 0.006$) and with binocular than with monocular vision ($p < 0.001$). Scheffe post-hoc comparison for correction reveals significant differences between all types of correction ($p < 0.001$) except between the naked eye and the 'Low' addition lens ($p = 0.25$).

In order to better quantify through-focus performance with all modes of correction, DOF (taken as negative trial lens power which reduced the VA to a specified level) was calculated from the visual acuity vs defocus curves of Figure 2, for two VA criteria of 0.0 (6/6, 20/20) and 0.1 logMAR (6/7.5, 20/25). To achieve this, second-order polynomials were fitted to VA vs defocus data for all individual subjects and lens conditions ($R^2 > 0.6$ in all cases). The DOF values for all combinations of aperture, viewing condition and correction for the two VA criteria are shown in *Figure 3*.

Average DOF was larger with the smaller (3 mm) than for the larger (6 mm) pupil and for binocular than for monocular viewing conditions. DOF increased as the addition of the MFCL correction increased for both VA criteria. A 2 × 2 × 4 (pupil aperture × viewing condition × correction) repeated measures ANOVA on DOF values based on the 0.1 logMAR acuity level revealed significant main effects of pupil aperture ($F_{1,11}$ = 16.4, $p = 0.002$), viewing condition ($F_{1,11}$=33.2, $p < 0.001$) and correction ($F_{3,33}$ =9.3, $p = 0.002$). Post-hoc analysis revealed statistically significant differences between all corrections except 'Naked eye' vs the 'Low' add ($p = 0.15$) and the 'Med' vs 'High' add MFCLs ($p = 0.23$). When ANOVA is performed only for the binocular data then the difference between the 'naked eye' and the 'Low' add lens reaches significance ($p = 0.046$).

To explore the possible impact of fourth-order ocular spherical aberration on performance with the different lenses at near, monocular VA for −3.00 D defocus was plotted as a function of each subject's Zernike C_4^0 coefficient for a 6 mm and a 3 mm pupil (*Figure 4*). For comparison, a value of +0.40 microns for C_4^0 corresponds to primary spherical aberration equal to 0.265 D mm^{-2}, i.e. in terms of corrections to −2.39 D of spherical aberration at the edge of a 6 mm pupil and −0.6 D at the edge of a 3 mm pupil. It can be seen that, with these centre-near designs (equivalent to negative spherical aberration), near VA tended to reduce as the ocular spherical aberration became more positive, although none of the individual regressions was significant at the $p = 0.05$ level.

Table 1. Mean (S.D.) visual acuity, measured in logMAR, for monocular (a) and binocular (b) observation at each condition tested

	Naked eye		Low Add CL		Medium add CL		High add CL	
Defocus	3 mm	6 mm	3 mm	6 mm	3 mm	6 mm	3 mm	6 mm
(a)								
−3.00	0.42 (0.08)	0.51 (0.08)	0.39 (0.16)	0.46 (0.10)	0.31 (0.08)	0.34 (0.11)	0.21 (0.10)	0.24 (0.07)
−2.50	0.32 (0.07)	0.37 (0.11)	0.28 (0.17)	0.34 (0.13)	0.19 (0.08)	0.25 (0.12)	0.10 (0.09)	0.12 (0.09)
−2.00	0.22 (0.13)	0.28 (0.12)	0.18 (0.12)	0.25 (0.15)	0.12 (0.09)	0.18 (0.10)	0.05 (0.09)	0.06 (0.07)
−1.50	0.12 (0.14)	0.20 (0.13)	0.10 (0.12)	0.13 (0.17)	0.00 (0.13)	0.11 (0.14)	−0.01 (0.10)	0.01 (0.11)
−1.00	0.01 (0.14)	0.06 (0.16)	−0.02 (0.08)	0.03 (0.15)	−0.04 (0.11)	0.00 (0.11)	−0.03 (0.10)	0.00 (0.14)
−0.50	−0.08 (0.22)	−0.06 (0.19)	−0.08 (0.09)	−0.05 (0.20)	−0.07 (0.15)	−0.01 (0.12)	−0.04 (0.15)	−0.01 (0.12)
0.00	−0.11 (0.11)	−0.12 (0.11)	−0.10 (0.10)	−0.06 (0.14)	−0.05 (0.11)	−0.01 (0.13)	−0.04 (0.15)	0.00 (0.10)
+0.50	−0.04 (0.11)	−0.01 (0.07)	−0.02 (0.09)	0.02 (0.08)	0.01 (0.09)	0.03 (0.09)	0.01 (0.06)	0.02 (0.09)
+1.00	0.13 (0.10)	0.18 (0.13)	0.08 (0.12)	0.11 (0.14)	0.04 (0.09)	0.07 (0.08)	0.09 (0.09)	0.09 (0.09)
+1.50	0.27 (0.15)	0.36 (0.15)	0.14 (0.12)	0.22 (0.17)	0.12 (0.09)	0.13 (0.12)	0.11 (0.11)	0.15 (0.06)
+2.00	0.42 (0.19)	0.45 (0.18)	0.22 (0.12)	0.28 (0.22)	0.18 (0.17)	0.22 (0.14)	0.16 (0.18)	0.24 (0.11)
+2.50	0.47 (0.16)	0.57 (0.17)	0.29 (0.15)	0.38 (0.24)	0.24 (0.17)	0.31 (0.16)	0.21 (0.18)	0.30 (0.15)
+3.00	0.53 (0.21)	0.61 (0.21)	0.37 (0.18)	0.49 (0.24)	0.28 (0.19)	0.41 (0.21)	0.28 (0.18)	0.41 (0.15)
(b)								
−3.00	0.36 (0.09)	0.42 (0.08)	0.33 (0.14)	0.40 (0.08)	0.21 (0.09)	0.24 (0.22)	0.12 (0.09)	0.16 (0.05)
−2.50	0.28 (0.07)	0.33 (0.08)	0.25 (0.16)	0.32 (0.08)	0.12 (0.08)	0.12 (0.14)	0.03 (0.09)	0.07 (0.06)
−2.00	0.17 (0.12)	0.21 (0.10	0.13 (0.16)	0.22 (0.09)	0.03 (0.10)	0.06 (0.14)	−0.01 (0.09)	0.00 (0.12)
−1.50	0.07 (0.13)	0.12 (0.12)	0.04 (0.11)	0.09 (0.12)	−0.05 (0.11)	−0.01 (0.11)	−0.06 (0.09)	−0.05 (0.09)
−1.00	−0.03 (0.14)	0.01 (0.15)	−0.04 (0.06)	−0.02 (0.15)	−0.05 (0.10)	−0.05 (0.07)	−0.05 (0.10)	−0.03 (0.12)
−0.50	−0.11 (0.19)	−0.09 (0.15)	−0.10 (0.05)	−0.08 (0.17)	−0.09 (0.11)	−0.06 (0.05)	−0.06 (0.08)	−0.03 (0.11)
0.00	−0.14 (0.12)	−0.14 (0.10)	−0.14 (0.07)	−0.10 (0.12)	−0.09 (0.11)	−0.04 (0.07)	−0.06 (0.09)	−0.04 (0.10)
+0.50	−0.09 (0.06)	−0.06 (0.07)	−0.06 (0.08)	−0.04 (0.05)	−0.03 (0.05)	0.00 (0.05)	−0.03 (0.07)	0.00 (0.07)
+1.00	0.03 (0.11)	0.09 (0.12)	0.04 (0.11)	0.04 (0.08)	−0.01 (0.09)	0.02 (0.07)	0.02 (0.08)	0.05 (0.08)
+1.50	0.16 (0.14)	0.25 (0.15)	0.08 (0.10)	0.15 (0.16)	0.03 (0.05)	0.09 (0.11)	0.05 (0.10)	0.09 (0.06)
+2.00	0.28 (0.18)	0.35 (0.20)	0.15 (0.11)	0.24 (0.22)	0.12 (0.10)	0.19 (0.14)	0.09 (0.15)	0.19 (0.08)
+2.50	0.35 (0.17)	0.42 (0.19)	0.21 (0.11)	0.28 (0.22)	0.15 (0.11)	0.26 (0.14)	0.16 (0.12)	0.25 (0.12)
+3.00	0.39 (0.20)	0.55 (0.22)	0.27 (0.11)	0.38 (0.24)	0.23 (0.13)	0.32 (0.22)	0.21 (0.12)	0.33 (0.15)

When the data for the 3 CL designs were grouped together, a linear correlation was found between VA at −3.00 D defocus (simulating performance at near) and the subject's ocular spherical aberration ($R^2 = 0.20$, $p = 0.005$ for 6 mm data, $R^2 = 0.11$, $p = 0.04$ for 3 mm data), with the eyes exhibiting the higher positive spherical aberration experiencing lower VAs (*Figure 5*). In contrast, no correlation was found for VA at 0.00 D defocus (distance vision).

We note, however, that the significance of some of these apparent correlations in *Figure 5* may be exaggerated. The data samples are not statistically independent, since each individual provides three measurements with the three lenses tested. The Intra-class correlation coefficient (ICC) for the simulated distant VA (for 6 mm pupil) is 0.05, so we would not expect the fact that the subjects are the same to affect the analysis. On the other hand, the ICC for the simulated near acuity (for 6 mm pupil) is 0.37, so the correlation between the variables cannot be ignored. However R^2 is high and p is very small (0.005) and it is not very likely that the correlation leads to incorrect inferences.

Discussion

The performance of all contact lens designs for the correction of presbyopia is primarily dependent on the enhancement of the DOF that they provide to counteract the loss of accommodation. This study shows that both through-focus visual acuity and the resulting DOF improve with these aspheric multifocal contact lenses, with the effect being more pronounced for small pupils and binocular vision. On the other hand, vision at best-focus (at distance) is always better with the 6 mm pupil diameter. It is also demonstrated that performance with simultaneous image aspheric CLs depends on the inherent ocular spherical aberration, with the centre-near profiles used offering better near vision to patients who exhibit negative spherical aberration.

These effects can be understood by considering the optical changes involved. Nominally, simultaneous viewing of in-focus and out-of-focus images must degrade vision by reducing retinal image contrast,[6,10] with the extent of contrast loss being upon the relative amounts of in-focus to out-of-focus light incident onto the retina. This balance is

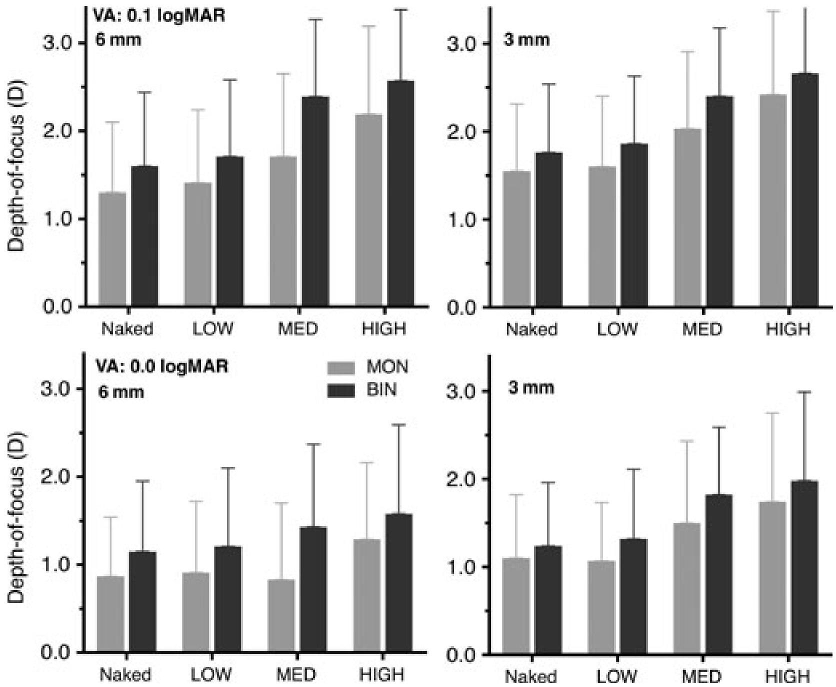

Figure 3. Average values of depth-of-focus, defined as the dioptric range, taken as the negative trial lens power for which the visual acuity remains better than either 0.0 logMAR (6/6, lower plots) or 0.1 logMAR (6/7.5, upper plots). 'Naked' refers to the naked eye condition, 'Low', 'Medium' and 'High' to the three MFCLs. The light grey bars refer to monocular conditions, the dark grey bars to binocular conditions. Error bars represent ± 1 S.D.

known to depend on interaction of light-dependent changes in pupil diameter with lens design.[7,11,19] Since centre-near designs provide greater power in the lens centre (see *Figure 1*), due to the negative spherical aberration, it is expected that smaller pupils, associated with near vision, will result in enhanced visual acuity at near, especially when high addition lenses are used. In contrast, small pupils will tend to compromise distance acuity.

Better performance was achieved at all conditions tested with binocular compared to monocular vision. It is evident that perceptual processes, such as binocular summation, enhance the interpretation of superimposed multiple images on the retina. It has recently been shown that binocular viewing improves visual perception of out-of-focus images to a much greater extent than it does for in-focus images.[23] This contrasts with monovision correction, in which perceptual summation from the two eyes is expected to be minimal. The visual improvement under binocular conditions cannot be predicted by using purely objective and computational techniques to simulate retinal image quality.

Performance for near, as well as the effective DOF, was also found to correlate with the inherent ocular aberrations of each participant. For example, performance with lenses for near was limited by the inherent positive spherical aberration found in most eyes because the effective add of any centre-near lens was reduced (see *Figures 4 and 5*). On the other hand, eyes with negative spherical aberration showed better performance for near. These results are in agreement with theoretical and computational studies,[11,12,29–31] which also suggested that inter-subject differences in ocular spherical aberration might determine the effectiveness of any aspheric multifocal design.

Although optimal VA was achieved with zero defocus (*Figure 1*) vision remained good (better than 0.1 logMAR, 6/7.5, 20/25 equivalent) up to around +1.00 D of positive defocus. It could, then, be argued that, if slightly compromised distance vision could be tolerated, improved near vision could be achieved by slightly over-plussing the nominal correction.

It should be stressed that good lens centration and relatively limited lens movement are necessary prerequisites for a successful visual outcome with multifocal contact lenses. With decentration, the retinal image changes markedly, resembling that produced by conventional oblique astigmatism.[7,29] The effect of decentration is more pronounced for distance vision and for larger pupil diameters.[10]

No attempt was made in the present study to explore adaptation effects. One feature of any type of presbyopic correction is that visual performance may improve with time. Functionality of any of the simultaneous image

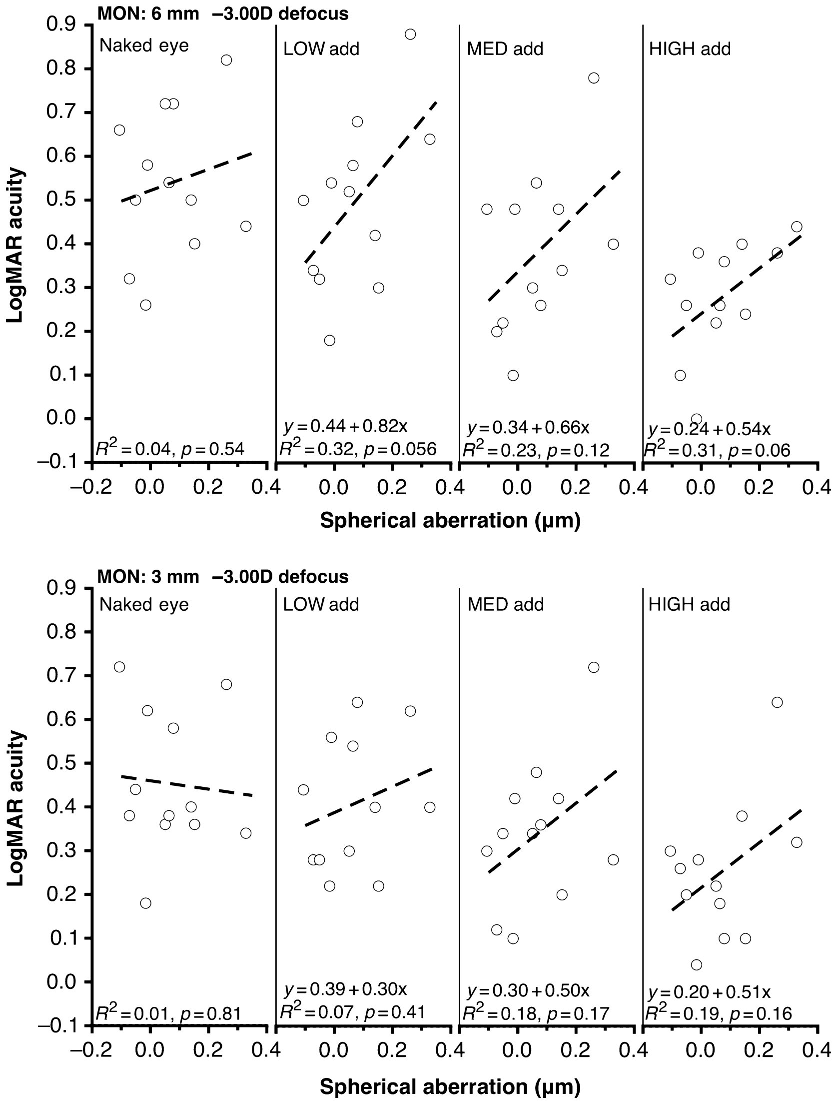

Figure 4. Visual acuity (logMAR) for individual subjects at −3.0 D defocus (i.e. at an equivalent viewing distance of 32 cm) as a function of their Zernike fourth-order spherical aberration coefficient C_4^0 for a 6 mm (upper) and a 3 mm (lower) pupil. Parameters for linear regression fits are shown.

designs should also be governed by blur adaptation, which is believed to occur at the cortical level.[32] Several authors have shown an improvement in acuity/sensitivity after limited periods of spherical defocus blur.[32–34] Wang and Ciuffreda[35] suggest that DOF may significantly improve after periods of blur adaptation. Interestingly, Jung and Kline[36] postulated that older observers' abilities to identify blurred text involves not only age-related optical changes, but also experience-mediated neural compensation. However, the neuro-adaptive responses in presbyopes have not been adequately studied to gain insight into the mechanisms involved. There is evidence, though, that the neural responses that underlie adaptation to transient blur are intact in the ageing visual system.[37]

We note that, although our study was carried out using young subjects under cycloplegia, in the practical case of early presbyopic MFCL wearers, small amounts of residual accommodation may result in increased effective DOF and improved near vision.[14]

In conclusion, this study has demonstrated that performance of aspheric multifocal CLs with centre-near design is enhanced for small pupils and with binocular compared to monocular vision. Moreover, coupling of the wearer's ocular spherical aberration with the aberration profiles provided by the multifocal CLs contributes to their functionality. Ideally, lenses should have customised profiles in order to fulfil the (near or distant) vision demands of each CL user. Further research using advanced behavioural methods

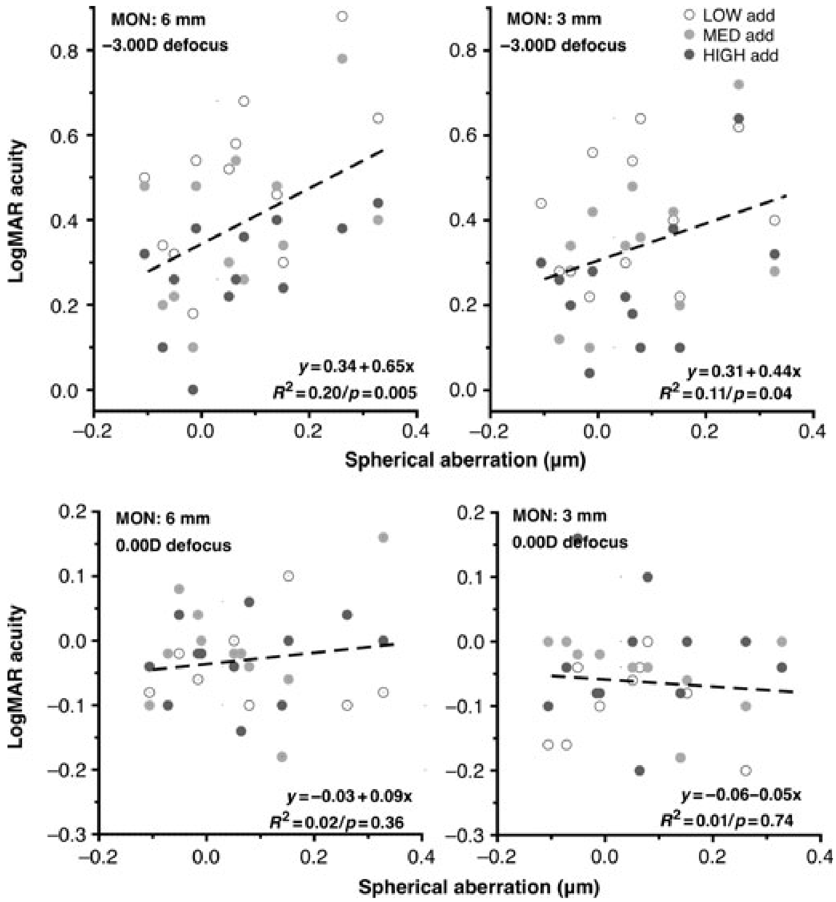

Figure 5. Monocular visual acuity (logMAR) at −3.00 D of defocus (upper graphs) and at best focus for distance (0.00 D, lower graph) as a function of the individual subject's fourth-order Zernike spherical aberration (C_4^0 for a 6 mm pupil) for the three multifocal contact lens corrections.

should be undertaken: this should simulate performance of individuals during their daily living tasks and activities, such as reading, driving and using hand-held devices.

Acknowledgements

We thank Joanna Moschandreas for her suggestions on the statistical analysis, George Kontadakis for the ocular aberration recordings and Panagiotis Kallinikos, co-supervisor of George Ntzilepis MSc thesis, for his comments on an earlier draft of the manuscript. Preliminary results of this work were presented at the 3rd EAOO annual meeting (Prague, 2011) and the 16th Symposium of ISCLR (Napa Valley, 2011).

Disclosure

Lenses were supplied free of charge by AMVIS, distributor of Ciba Vision products at the time of the study. There was no other financial support for this study from this company or others. All authors report no conflicts of interest.

References

1. Charman WN. Theoretical aspects of monovision contact lens correction. *Optician* 1980; 179: 9–22.
2. Josephson JE, Erickson P, Back A *et al.* Monovision. *J Am Optom Assoc* 1990; 61: 820–826.
3. Evans BJ. Monovision: a review. *Ophthalmic Physiol Opt* 2007; 27: 417–439.
4. Nayeb-Hashemi N, Yu EY & Azar DT. Correction of presbyopia with monovision. In: Presbyopia: Origins, Effects, and Treatment (Pallikaris IG, Plainis S & Charman WN, editors). SLACK Incorporated: New Jersey, 2012; pp. 143–149.
5. Bennett ES. Contact lens correction of presbyopia. *Clin Exp Optom* 2008; 91: 265–278.
6. Charman WN & Saunders B. Theoretical and practical factors influencing the optical performance of contact lenses for the presbyope. *J Brit Cont Lens Ass* 1990; 13: 67–75.
7. Kallinikos P, Santodomingo-Rubido J & Plainis S. Correction of presbyopia with contact lenses. In: Presbyopia: Origins, Effects, and Treatment (Pallikaris IG, Plainis S &

Charman WN, editors). SLACK Incorporated: New Jersey, 2012; pp. 127–137.
8. Morgan PB, Efron N & Woods CA. An international survey of contact lens prescribing for presbyopia. *Clin Exp Optom* 2011; 94: 87–92.
9. Benjamin WJ. Simultaneous vision contact lenses: why the dirty window argument doesn't wash. *Int Cont Lens Clinic* 1993; 20: 239–242.
10. Charman WN & Walsh G. Retinal images with centred aspheric varifocal contact lenses. *Int Cont Lens Clinic* 1988; 15: 87–93.
11. Bakaraju RC, Ehrmann K, Falk D, Ho A & Papas E. Optical performance of multifocal soft contact lenses via a single-pass method. *Optom Vis Sci* 2012; 89: 1107–1118.
12. Bakaraju RC, Ehrmann K, Ho A & Papas E. Inherent ocular spherical aberration and multifocal contact lens optical performance. *Optom Vis Sci* 2010; 87: 1009–1022.
13. López-Gil N, Castejón-Mochón JF, Benito A *et al.* Aberration generation by contact lenses with aspheric and asymmetric surfaces. *J Refract Surg* 2002; 18: S603–S609.
14. Plainis S, Atchison DA & Charman WN. Commenting on "Using Power Profiles to Evaluate Aspheric Lenses". *Cont Lens Spectrum* 2011; 15–17.
15. Legras R, Benard Y & Rouger H. Through-focus visual performance measurements and predictions with multifocal contact lenses. *Vision Res* 2010; 50: 1185–1193.
16. Móntes-Micó R, Madrid-Costa D, Radhakrishnan H, Charman WN & Ferrer-Blasco T. Accommodative functions with multifocal contact lenses: a pilot study. *Optom Vis Sci* 2011; 88: 998–1004.
17. Rajagopalan AS, Bennett ES & Lakshminarayanan V. Visual performance of subjects wearing presbyopic contact lenses. *Optom Vis Sci* 2006; 83: 611–615.
18. Richdale K, Mitchell GL & Zadnik K. Comparison of multifocal and monovision soft contact lens corrections in patients with low-astigmatic presbyopia. *Optom Vis Sci* 2006; 83: 266–273.
19. Bradley A, Abdul Rahman H, Soni PS & Zhang X. Effects of target distance and pupil size on letter contrast sensitivity with simultaneous vision bifocal contact lenses. *Optom Vis Sci* 1993; 70: 476–481.
20. Plainis S & Pallikaris IG. Ocular monochromatic aberration statistics in a large emmetropic population. *J Mod Opt* 2008; 55: 759–772.
21. Porter J, Guirao A, Cox IG & Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A Opt Image Sci Vis* 2001; 18: 1793–1803.
22. Ruiz-Alcocer J, Madrid-Costa D, Radhakrishnan H, Ferrer-Blasco T & Móntes-Micó R. Changes in accommodation and ocular aberration with simultaneous vision multifocal contact lenses. *Eye Contact Lens* 2012; 38: 288–294.
23. Plainis S, Petratou D, Giannakopoulou T, Atchison DA & Tsilimbaris MK. Binocular summation improves performance to defocus-induced blur. *Invest Ophthalmol Vis Sci* 2011; 52: 2784–2789.
24. Woods RL, Colvin CR, Vera-Diaz FA & Peli E. A relationship between tolerance of blur and personality. *Invest Ophthalmol Vis Sci* 2010; 51: 6077–6082.
25. Laretzaki G, Plainis S, Vrettos I, Chrisoulakis A, Pallikaris I & Bitsios P. Threat and trait anxiety affect stability of gaze fixation. *Biol Psychol* 2011; 86: 330–336.
26. Vogt A, Bateman K, Green T & Reindel B. Using Power Profiles to Evaluate Aspheric Lenses. *Cont Lens Spectrum* 2011.
27. Plainis S, Tzatzala P, Orphanos Y & Tsilimbaris MK. A modified ETDRS visual acuity chart for European-wide use. *Optom Vis Sci* 2007; 84: 647–653.
28. Thibos LN, Applegate RA, Schwiegerling JT & Webb R. Report from the VSIA taskforce on standards for reporting optical aberrations of the eye. *J Refract Surg* 2000; 16: S654–S655.
29. Charman WN & Walsh G. Retinal image quality with different designs of bifocal contact lenses. *J Brit Cont Lens Ass* 1986; 9: 13–19.
30. Plakitsi A & Charman WN. Comparison of the depth of focus with the nakes eye and with three types of presbyopic contact lens correction. *J Brit Cont Lens Ass* 1995; 18: 119–125.
31. Plakitsi A & Charman WN. Ocular spherical aberration and theoretical through-focus modulation transfer functions calculated for eyes fitted with two types of varifocal presbyopic contact lens. *Cont Lens Anterior Eye* 1997; 20: 97–106.
32. Mon-Williams M, Tresilian JR, Strang NC, Kochhar P & Wann JP. Improving vision: neural compensation for optical defocus. *Proc Biol Sci* 1998; 265: 71–77.
33. Cufflin MP, Mankowska A & Mallen EA. Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Invest Ophthalmol Vis Sci* 2007; 48: 2932–2939.
34. George S & Rosenfield M. Blur adaptation and myopia. *Optom Vis Sci* 2004; 81: 543–547.
35. Wang B & Ciuffreda KJ. Foveal blur discrimination of the human eye. *Ophthalmic Physiol Opt* 2005; 25: 45–51.
36. Jung GH & Kline DW. Resolution of blur in the older eye: neural compensation in addition to optics? *J Vis* 2010; 10: 7.
37. Elliott SL, Hardy JL, Webster MA & Werner JS. Aging and blur adaptation. *J Vis* 2007; 7: 8.