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ORIGINAL ARTICLE

The effect of multifocal contact lenses on the dynamic accommodation step response

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Abstract

Purpose: To measure the dynamic accommodation response (AR) to step stimuli with and without multifocal contact lenses (MFCLs), in emmetropes and myopes.

Methods: Twenty-two adult subjects viewed alternating distance (0.25D) and near (3D) Maltese crosses placed in free space, through two contact lens types: single vision (SVCL) or centre-distance multifocal (MFCL; +2.50D add). The AR level was measured along with near to far (N–F) and far to near (F–N) step response characteristics: percentage of correct responses, magnitude, latency, peak velocity and duration of step response.

Results: There was no difference between N–F and F–N responses, or between refractive groups in any aspect of the accommodation step response dynamics. The percentage of correct responses was unaffected by contact lens type. Through MFCLs, subjects demonstrated smaller magnitude, longer latency, shorter duration and slower peak velocity steps than through SVCLs. When viewing the near target, the AR through MFCLs was significantly lower than through SVCLs. When viewing the distance target with the MFCL, the focal points from rays travelling through the distance and near zones were approximately 0.004D behind and 2.50D in front of the retina, respectively. When viewing the near target, the respective values were approximately 1.89D behind and 0.61D in front of the retina.

Conclusion: The defocus error required for accommodation control appears not to be solely derived from the distance zone of the MFCL. This results in reduced performance in response to abruptly changing vergence stimuli; however, these errors were small and unlikely to impact everyday visual tasks. There was a decrease in ocular accommodation during near tasks, which has previously been correlated with a reduced myopic treatment response through these lenses. With MFCLs, the estimated dioptric myopic defocus was the largest when viewing a distant stimulus, supporting the hypothesis that the outdoors provides a beneficial visual environment to reduce myopia progression.

KEYWORDS
accommodation, contact lenses, myopia

INTRODUCTION

It is thought that retinal defocus, specifically hyperopic defocus, could be a contributing factor to myopic progression.[1–3] There is, however, some conflicting evidence about the accuracy of the accommodation response (AR) in myopes compared to emmetropes; younger myopes have been reported to have larger lags of accommodation than their emmetropic counterparts.[4–9] Conversely, no significant difference between refractive groups has also been reported.[10–12] A lag of accommodation produces hyperopic defocus at the retina, which has been proposed to be a driver for axial elongation and subsequent myopia development and progression.[13–15]

Multifocal contact lenses (MFCLs) are one myopia management method employed to reduce the progression of myopia by altering the amount and type of defocus present across the retina. There are various, possibly interacting, ways in which MFCLs may provide myopic defocus and thus a protective effect, thereby reducing progression. Their use results in greater positive spherical aberration, which causes an increase in the ocular depth of focus (DoF), thought to provide a countermeasure to the increased lag of accommodation in myopes.[16,17] Further, inducing myopic retinal defocus with MFCLs is widely believed to reduce myopic progression, as demonstrated in monkeys[18,19] and humans.[20–25] Last is the concept of simultaneous vision whereby these lenses produce multiple focal points along the visual axis. Any myopic defocus present may affect eye growth signals and reduce axial elongation.

The amount of myopic retinal defocus induced by a MFCL varies between individuals as it depends on several anatomical factors, for example, corneal and retinal shape, but is also affected substantially by the individual's AR. Some studies have measured similar ARs when viewing a near target through either MFCLs or single vision contact lenses (SVCLs),[26,27] suggesting that subjects rely entirely on the distance zone of the MFCL.[26–28] On the other hand, a reduced AR through MFCLs has led to the hypothesis that a combination of both the distance and near zones,[29,30] or indeed part(s) of the transition zone between the two, determines the AR.[29] A recent study by Cheng et al.[30] reported a correlation between a reduced AR and the consequent increase in myopia progression.

In contrast to the static viewing conditions described above, in a real-world situation the stimulus vergence and retinal defocus levels change constantly and abruptly. Some previous investigations of accommodation to abrupt, step-wise changes in stimulus vergence have identified differences in myopes,[31–33] while others have not.[34–36] The variation in methodologies and results reported in these studies make it difficult to conclude whether refractive group differences exist when making dynamic steps. Strang et al.[34] conducted a comprehensive investigation using steps of various sizes and targets with different spatial frequencies. While there were similarities in the step response characteristics between different refractive groups, myopes conducted fewer responses to high spatial frequency targets. MFCLs introduce varying levels of defocus with the presence of a progression zone and multiple simultaneous focal points, which reduces retinal image quality particularly affecting high spatial frequency information, making refractive group differences interesting to investigate. Therefore, the aim of this study was to investigate the accommodation step response when viewing through MFCLs in emmetropic and myopic observers.

Key points

- Multifocal contact lenses for myopia management induce small inaccuracies in the accommodation step response which are unlikely to affect everyday tasks.
- Multifocal contact lenses appear to reduce the magnitude of the accommodation response at near and may increase the amount of myopigenic hyperopic defocus during near work.
- When worn for myopia management, multifocal contact lens wearers should be encouraged to spent time outdoors to increase myopic retinal defocus and maximise the myopia control effect.

METHODOLOGY

Subject criteria

Subjects were aged 18–30 years to ensure an adequate accommodative amplitude (all had at least 8D of accommodation). Emmetropia was classified as a mean spherical equivalent refractive error (MSE; sphere +0.50*cylinder) between −0.25 and +0.75D, while all myopic subjects had a MSE ≤−0.75D. Ten emmetropes and 12 myopes were recruited and all had a maximum cylindrical correction of 0.75 DC.

This study was approved by the Glasgow Caledonian University, School of Health and Life Sciences Ethics Committee and was conducted in accordance with the Declaration of Helsinki.

Set-up

A modified open-field, infrared autorefractor (Shin-Nippon SRW-5000, no longer manufactured and superseded by models from Grand Seiko: grandseiko.com/en/ophthalmic) was used in dynamic mode to record the continuous AR. This autorefractor allows binocular viewing and produces accurate and repeatable results.[37–40] Two Maltese cross targets were back-illuminated with light-emitting diodes (LEDs) inside light boxes (distance contrast: 81%, near contrast: 62.4%; distance luminance: 212 cd/m^2, near luminance: 224 cd/m^2) with the same angular subtense (1.98°) were set up at distance of 4 m and 33 cm. Figure 1 shows the experimental set-up. The left eye converged to view the near target.

A minimum pupil diameter of 2.9 mm is required to obtain an accurate measurement using the Shin-Nippon SRW-5000.[38] The distance zone of the contact lens has a diameter of 3.02 mm,[41] and as a result, a small pupil or MFCL movement could lead to the progression/near zones

FIGURE 1 Schematic representation of the subject's right (RE) and left eye (LE) with target alignment. Both near (33 cm) and distance (4 m) targets were size-matched Maltese cross targets, each displayed in an internally illuminated light box. The subject viewed the distance target with the LE with the contact lens (CL) in place, via the 50/50 mirror. The near target was at 33 cm from the eye. Step changes in stimulus vergence were achieved by illuminating these targets in turn.

of the CL encroaching on the measurement area of the autorefractor, thus influencing the measurement. Therefore, measurements were taken without the MFCL in place. Accordingly, measurements were taken from the right eye, which had no CL in place, and was occluded with an infrared transmitting filter.

For accurate recording from the right eye, it was vital that this eye did not move during the measurement, particularly when the targets switched between near and distance. The set-up was such that the near target was aligned with the visual axis of the subjects' right eye, and the left eye converged to view it. The distance target was positioned perpendicular to the near target and in line with the 50/50 mirror. The mirror was adjusted so that the subject did not experience any movement in the vertical/horizontal location of the Maltese cross target when the near and distance targets were illuminated alternately, and the right eye did not move during the experiment.

The room lights were dimmed (luminance: 34.47 cd/m^2) to reduce miosis, but were bright enough to maintain both retinotopic and spatiotopic accommodation cues. Subjects adapted to this light level for at least 10 minutes prior to any recording of the AR. Stimulus presentation was controlled by software (LabVIEW, 2011, Version 11.0, ni.com) and targets alternated approximately every 10 seconds.

Contact lens type

Two contact lens types were used. A SVCL (Biofinity, coopervision.co.uk) and a MFCL with a +2.50D near addition (Biofinity Multifocal, Centre Distance, coopervision.co.uk). This MFCL has a central zone diameter of 3.02 mm based on measured power profiles leading to an intermediate zone that graduates into the near addition power, located more peripherally.[41]

The power of the CL in each eye was calculated using the MSE from a distance autorefractor measurement. The subjects wore the same type of CL in both eyes and were given 30 min to adapt prior to data collection. Throughout adaptation, subjects walked around indoors and outdoors and were encouraged to make normal eye movements and accommodation steps throughout (e.g., read from a book, read signs in the distance, etc.) The order of the CL type was randomised, and lenses were fitted in line with the manufacturer's guidelines. The CL was removed from the subject's right eye prior to measurements being taken. All subjects were assessed and deemed to have normal binocular vision and amplitude of accommodation as part of subject recruitment.

Calibration and recording

An average of 10 static autorefractor measurements was taken from the uncorrected right eye while the subject viewed the distance target to gain a measure of their refractive error. These static readings were used to calibrate the autorefractor for use in dynamic mode.[42]

Once the subject was aligned and set up, they were given a short practice and were instructed to ‘keep each of the targets clear’ during the experiment. Continuous recording of the AR commenced at a sampling rate of 60 Hz. Approximately 120 s of data was recorded when viewing through each CL type containing a minimum of 10 step responses with the stimulus changing from far to near (F–N) and near to far (N–F). Recordings were acquired using LabVIEW software and were time-locked with the stimulus. Analysis of the response traces was performed offline using Microsoft Excel (Microsoft.com) functions.

Analysis of accommodation step response dynamics

The process and algorithm used for the analysis of the steps has been used previously and is described in detail by Strang et al.[34] After smoothing with a 10 Hz Butterworth filter, blinks were removed, and the start and end points of each step response determined automatically when the velocity of the AR fell below 1D/s for 0.12 s. Within each recording of the AR, responses to the target were deemed either a correct step or no step. If not a step, then a null response or the presence of slow drift was manually noted. In the event of slow drift, the direction of the drift was denoted as either correct (e.g., F–N in the event of a F–N step), wrong (e.g., N–F in the event of a F–N step) or variable (both correct and wrong).

For each identified step response, the algorithm recorded the following parameters: latency, step duration and peak velocity of the correct steps. For each correct step, the magnitude of the AR was calculated as the difference between the average 1 s of the response before and after the step was made (Figure 2). The presence of slow drift after a step was also noted manually and categorised in the same way as described above, that is, correct, wrong or variable. For every subject, all of the response parameters were averaged within one contact lens type. This was then averaged across subjects within each refractive group.

Measurement of accommodation response

The distance and near AR levels were determined by averaging 1-s portions of the response trace before and after each step change (Figure 2). This was done for all steps recorded in each trial for the two types of CL. These 1-s portions of the response were then averaged as the overall mean AR at distance or near viewing for each refractive group. The mean distance and near ARs were later used to calculate the retinal defocus experienced by subjects through the MFCLs.

Retinal defocus

The distance and near AR levels, derived from all the step responses, were used to estimate the dioptric retinal defocus for each subject using Equation 1(a,b).

$$\begin{gathered}\text{(a) Retinal defocus}_{\text{SV}} = \text{AS} - \text{AR}\\ \text{(b) Retinal defocus}_{\text{MFCLD}} = \text{AS-AR}\\ \text{(c) Retinal defocus}_{\text{MFCLN}} = \text{AS} - \text{AR} - \text{ADD}\\ \text{Where: AS} = \frac{1}{\text{Target Distance (m)}}\end{gathered} \tag{1}$$

Calculation of retinal defocus through single vision contact lenses (SVCLs) and multifocal contact lenses (MFCLs), where the accommodative stimulus (AS) is 1/target distance (metres), the accommodative response (AR) is the measured refractive error (dioptres) and ADD represents the near addition power in the MFCLs. For the SVCL and through the distance zone of the MFCL, this is calculated using Equation 1(a). The defocus through the near zone of the MFCL was calculated using Equation 1(b). Negative and positive values of retinal defocus represent myopic and hyperopic defocus, respectively.

The two main power zones (D and N) in the MFCL simultaneously created two corresponding dioptric retinal defocus values. These were estimated using Equation 1(b,c) and compared to the estimated dioptric defocus when viewing through the SVCL. For all estimations of dioptric retinal defocus, negative and positive values represent myopic and hyperopic defocus, respectively.

Statistical analysis

When investigating the parameters of the dynamic step response, a three-factor—CL type (SV; MF), refractive group (emmetrope; myope) and step direction (F–N; N–F)—multivariate ANOVA was conducted (SPSS, Version 26, ibm.com). As there was no significant difference in the AR between the refractive groups nor step direction, data for refractive group and step direction were later combined.

When analysing the characteristics of the null step response, a two-factor—CL type (SV; MF) and no step type (null, drift correct direction, drift wrong direction and drift variable direction)—multivariate ANOVA was applied. When analysing the characteristics of the slow drift after a correct step response, a two-factor—CL type (SV; MF) and slow drift type (drift correct direction, drift wrong direction and drift variable direction)—multivariate ANOVA was applied.

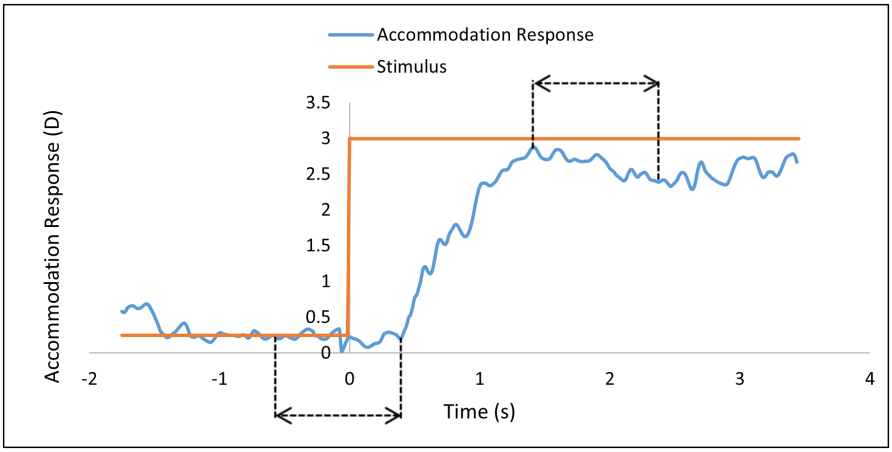

FIGURE 2 Example step response for a target change from far-to-near (0.25–3D). Mean near and far accommodation response levels were obtained by averaging 1-s portions of the response trace before and after each step change (exemplified by the arrowheads and dotted lines). The average distance and near accommodative response (AR) were then used to calculate the retinal defocus when viewing either the distance or the near target as demonstrated in Equation 1.

When investigating the steady-state AR, a three-factor—CL type (SV; MF), refractive group (emmetrope; myope) and target distance (distance; near)—multivariate ANOVA was applied. For all above statistics, Bonferroni adjustments were made for multiple comparisons. Pairwise comparisons were made between all sets of variables.

RESULTS

Subject information

Subject details are shown in Table 1. There was no significant difference in cylindrical power ($p = 0.72$) or pupil diameter ($p = 0.27$) between refractive groups.

Accommodation step response dynamics

Figure 3a shows the percentage of correct steps made for both the SVCL and MFCL types for the F–N and N–F directions for myopes and emmetropes. Step direction (percentage correct steps: $F_{1,39} = 0.14$, $p = 0.71$; step magnitude: $F_{1,39} = 1.48$, $p = 0.23$; latency: $F_{1,39} = 0.006$, $p = 0.94$; peak velocity: $F_{1,39} = 0.19$, $p = 0.67$; step duration: $F_{1,39} = 0.58$, $p = 0.45$) and refractive group (percentage correct steps: $F_{1,39} = 2.16$, $p = 0.15$; step magnitude: $F_{1,39} = 0.41$, $p = 0.53$; latency: $F_{1,39} = 0.04$, $p = 0.85$; peak velocity: $F_{1,39} = 0.14$, $p = 0.71$; step duration: $F_{1,39} = 0.07$, $p = 0.80$) did not significantly affect any of the five response parameters shown in Figure 3. Therefore, the data from the emmetropes and myopes as well as N–F and F–N steps were combined. Figure 3b–e shows group mean step response magnitude, latency, peak velocity and step duration. Mean and standard deviation values are shown in Table 2.

CL type did not significantly influence the percentage of correct steps made ($F_{1,39} = 4.17$, $p = 0.05$). The magnitude of the step response was found to be significantly larger in SVCL than in MFCL ($F_{1,39} = 67.57$, $p = 0.001$). Latency was significantly shorter in the SVCL than in the MFCL ($F_{1,39} = 25.83$, $p = 0.001$). Peak velocity was significantly faster in the SVCL ($F_{1,39} = 8.93$, $p = 0.005$) and the duration of the step response was significantly longer in the SVCL than in the MFCL ($F_{1,39} = 9.66$, $p = 0.004$).

Details of the behaviour of the no step responses are shown in Figure 4, which indicates the percentage of responses that were null steps and the direction in which the AR drifted after the accommodative stimulus change. There was no difference in the type of no step response between CL types ($F_{1,84} = 2.13$, $p = 0.15$). There was a significant difference between the percentage of responses through both CL types (SVCL: $F_{3,84} = 5.61$, $p = 0.001$; MFCL: $F_{3,84} = 17.25$, $p < 0.001$). Subjects drifted significantly more in the correct direction compared with other types of no step response through MFCLs (pairwise comparison, $p < 0.001$ for all comparisons). Through the SVCL, subjects drifted significantly more in the correct direction than in the variable (pairwise comparison, $p = 0.005$) and wrong (pairwise comparison, $p = 0.003$) direction, but not the null responses (pairwise comparison, $p = 0.29$).

After a correct step was made, slow drift occurred in 36.9 ± 19.5% of SVCL and 40.9 ± 23.7% of MFCL steps. Figure 5 shows the direction of this slow drift, as a percentage of the steps that exhibited slow drift after the correct step, in the correct, wrong and variable directions. There was no effect of CL type worn in the direction of slow drift ($F_{1,63} = 0.56$, $p = 0.47$). There was a significant difference between the amount of slow drift in different directions in both CL types (SVCL: $F_{2,63} = 21.56$, $p < 0.001$; MFCL: $F_{2,63} = 5.96$, $p = 0.004$). Pairwise comparisons showed significantly more slow drift in the correct direction than in the wrong ($p < 0.001$) and variable directions ($p < 0.001$) through the SVCLs, with no difference between the variable and wrong drifts ($p = 0.15$). While wearing MFCL, subjects drifted significantly more in the correct direction than in the wrong direction ($p = 0.003$); however, there was no significant difference between the percentage of drift in the correct direction compared to variable ($p = 0.17$) or variable versus wrong ($p = 0.41$).

TABLE 1 Details for both myopic and emmetropic refractive groups.

	Myopes	Emmetropes
Number of subjects	12	10
Male	3	3
Female	9	7
Caucasian	7	3
Other[a]	5	7
MSE (mean ± SD (min to max); DS)	−3.58 ± 1.82 (−0.88 to −6.13)	+0.33 ± 0.21 (0.06 to −0.63)
Distance pupil diameter (mean ± SD (min to max); mm)	4.96 ± 0.81 (4.00 to 6.00)	5.55 ± 0.69 (4.50 to 6.00)
Average subject age (mean ± SD (min to max); years)	23.3 ± 4.1 (19 to 30)	22.4 ± 4.5 (18 to 30)

Note: Mean spherical equivalent refractive error (MSE) = sphere power + (0.5*cylinder power). Distance pupil diameter is reported under experimental conditions (dimmed illumination).

Abbreviation: DS, dioptre sphere.

[a] This group consists of subjects of Asian British and mixed ethnicity. Mean values are given ± standard deviation (SD) of the mean.

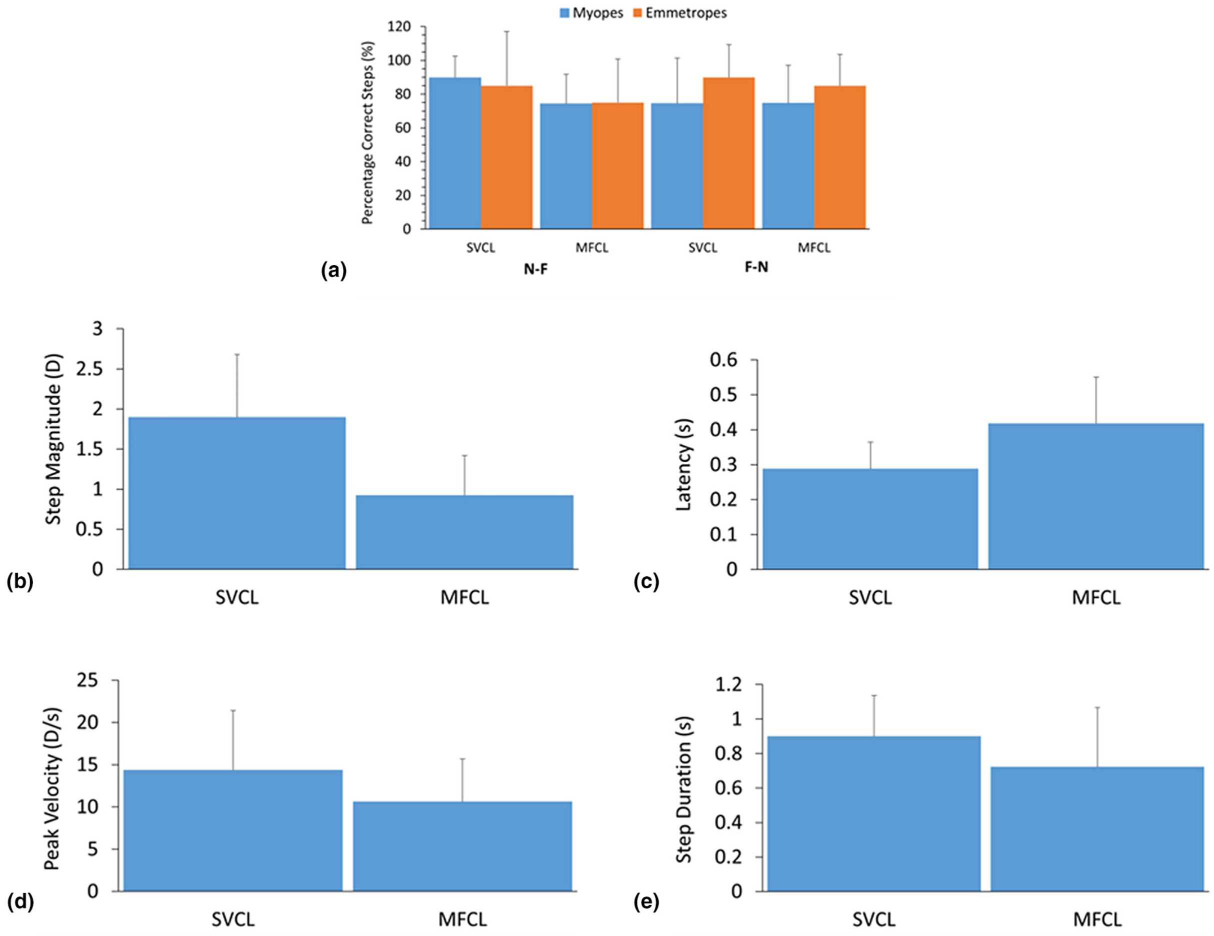

FIGURE 3 The step characteristics of all observers: (a) the average percentage of steps made in the correct direction in the far to near (F–N) and near to far (N–F) step direction by both refractive groups in both contact lens types, (b) the magnitude of the step response, (c) the latency of the step response, (d) the peak velocity achieved during the step response and (e) the duration of the step response. (b–e) are shown with F–N and N–F step directions and refractive groups combined. Error bars are standard deviations of the mean. MFCL, multifocal contact lens; SVCL, single vision contact lens.

TABLE 2 Summary table displaying values from previous studies and the present experiment measuring steps including percentage of steps made, latency, duration, velocity and amplitude.

Authors (Year of publication)	Correct steps (%)	Latency (s)	Duration (s)	Peak velocity (D/s)	Response step magnitude (D) (stimulus step magnitude (D))
Schaeffel et al. (1993)[35]			1	11.1	
Culhane and Winn (1999)[32]		0.23	0.91		
Seidel et al. (2003)[36]	92.9	0.3			
Strang et al. (2011)[34]	63	0.37	0.87	9.01	2.09 (3)
Kasthurirangan and Glasser (2005)[43]	94	0.23			
Montés-Micó et al. (2011)[26]					2.00 (2.75)
Average of above studies (mean ± SD)	83.3 ± 17.59	0.28 ± 0.07	0.93 ± 0.07	9.37 ± 1.58	2.05 ± 0.06 (2.87)
This experiment—SVCL (mean ± SD)	82.49 ± 26.86	0.29 ± 0.07	0.90 ± 0.24	14.33 ± 7.09	1.89 ± 0.78 (2.75)
This experiment—MFCL (mean ± SD)	76.942 ± 20.291	0.42 ± 0.13	0.72 ± 0.34	10.61 ± 5.01	0.92 ± 0.50 (2.75)
This experiment—all conditions (mean ± SD)	79.72 ± 24.1	0.35 ± 0.13	0.81 ± 0.31	12.45 ± 6.39	1.40 ± 0.81 (2.75)

Note: The average of these is also shown alongside values obtained in this experiment for single vision contact lenses (SVCLs) and multifocal contact lens (MFCL) types.

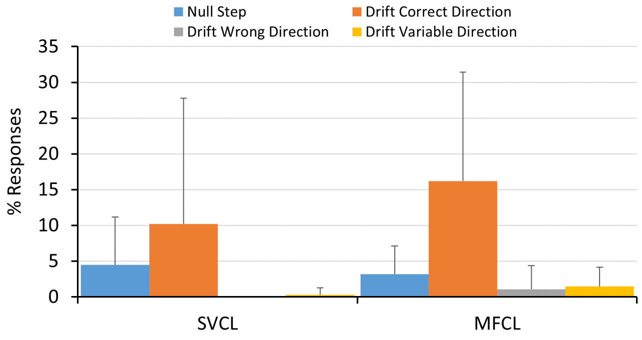

FIGURE 4 The percentage of null steps and those with slow drift in the correct, wrong and variable directions. Error bars are standard deviations of the mean. MFCL, multifocal contact lens; SVCL, single vision contact lens.

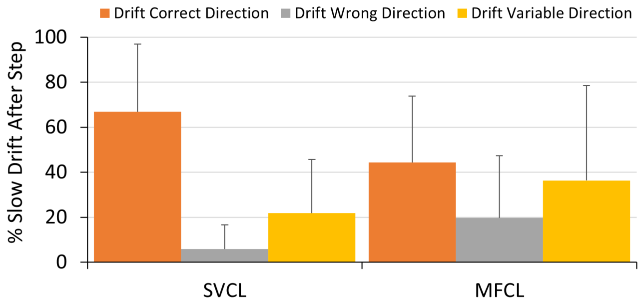

FIGURE 5 The percentage of slow drift after a correct step in the correct, wrong and variable direction is shown. Error bars are standard deviations of the mean. MFCL, multifocal contact lens; SVCL, single vision contact lens.

Accommodation response (AR) level

The AR for all myopic and emmetropic subjects is shown in Figure 6. There was no significant difference in AR depending upon step direction ($F_{1,79} = 2.07$, $p = 0.15$), so these data were combined. Findings are shown for both CL types, while subjects were viewing the distance and near targets.

No significant difference in AR level was found between the refractive groups for either CL type, when viewing either distance (SVCL: $F_{1,40} = 0.89$, $p = 0.35$; MFCL: $F_{1,40} = 2.65$, $p = 0.11$) or near target (SVCL: $F_{1,40} = 0.95$, $p = 0.34$; MFCL: $F_{1,40} = 2.49$, $p = 0.12$). While viewing the near target, the AR level through the SVCL was significantly higher than the MFCL in both refractive groups (emmetropes: $F_{1,40} = 16.49$, $p < 0.001$; myopes: $F_{1,40} = 13.18$, $p < 0.001$). There was no difference between CL types in either refractive group when viewing the distance target (emmetropes: $F_{1,40} = 0.003$, $p = 0.96$; myopes: $F_{1,40} = 0.98$, $p = 0.33$).

Retinal defocus

There was no significant difference between refractive groups in the AR analysis above. Hence, refractive group data were combined for the calculation of retinal defocus levels. Figure 7 displays the average amount of dioptric retinal defocus along the visual axis estimated for SV and MFCLs, while viewing both distance and near targets in all subjects. Dioptric retinal defocus was plotted separately for the distance and near zones of the MFCL (MFCL D and MFCL N, respectively).

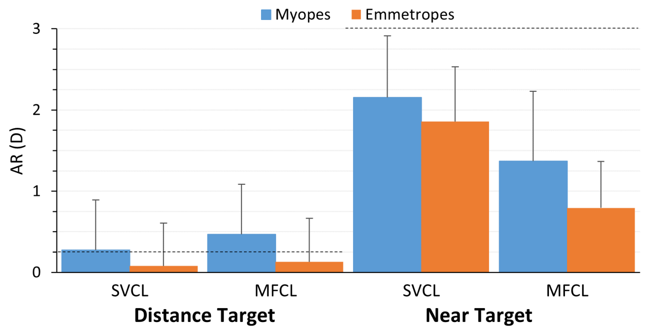

FIGURE 6 The accommodation response is shown for subjects in myopes and emmetropes and in the MFCL and SVCL types while viewing the distance (0.25D) and near (3D) target. The accommodative stimulus for the distance (+0.25D) and near target (+3.00D) is denoted by the dotted lines. Error bars are standard deviations of the mean. MFCL, multifocal contact lens; SVCL, single vision contact lens.

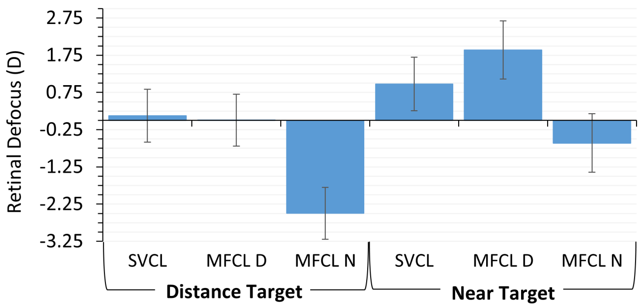

FIGURE 7 Estimated dioptric retinal defocus levels along the visual axis while viewing the distance and near target through a single vision contact lens (SVCL), the distance zone of the multifocal contact lens (MFCL D) and the near zone of the multifocal contact lens (MFCL N). At distance viewing, MFCL N represents the estimated dioptric position of the light rays through the near zone of the MFCL. At near viewing, the MFCL D represents the estimated dioptric position of the light rays through the distance zone of the MFCL. Negative and positive values of retinal defocus represent myopic and hyperopic defocus, respectively. Error bars are standard deviations of the mean.

The SVCL and the MFCL D were estimated to produce a small amount of hyperopic retinal defocus at distance viewing which increased with near viewing. The MFCL N produced myopic defocus for both distance and near viewing. The magnitude of the defocus was significantly larger for near targets than distance targets (SV: $F_{1,40} = 15.58$, $p < 0.001$; MFCLs: $F_{1,40} = 8.08$, $p = 0.007$). Substantial amounts of central axial myopic defocus were produced by the MFCL N zone at both distance and near; on average, 2.50D for the distance target and 0.61D for the near target. Subjects experienced significantly more myopic defocus through the MFCL N zone when viewing the distance target than the near ($F_{1,40} = 420.44$, $p < 0.001$).

DISCUSSION

Step responses and CL types

The results show that 79.7% of step responses made by all subjects were in the correct direction. Table 2 provides a summary of all step parameters obtained in this experiment and those derived from previous literature. A value of 79.7% is in line with previous reports with an average across studies of 83.3 ± 17.59% correct steps made,[31,34,43] demonstrating that wearing a MFCL does not influence the subject's ability to make an accommodation step in the correct direction.

All step response parameters recorded in the SVCL type compared well with previously reported values. Latencies were in line with those reported for real, high-contrast stimuli presented in free space.[31,32,43] A 31% increase in mean latency with the MFCL, compared with the SVCL, is likely to be the result of the increased (higher order) aberrations produced by the Biofinity MFCL.[44–46] These aberrations will result in an increased DoF, which will reduce the retinotopic input error to the accommodation control system, and in turn affect the generation of the system's acceleration pulse and delay the onset of the response.[47]

In this experiment, the magnitude, duration and maximum velocity of the step responses were also influenced by CL type. On average, step response magnitude with the MFCL was approximately 51% lower than that achieved with the SVCL. This was accompanied by a 26% reduction in peak velocity and 20% reduced response duration. For the distance target, the mean AR level appeared to be close to the stimulus demand for both the SVCL and MFCLs. This is perhaps not surprising; the centre-distance design of the MFCL, whose power profile provides over 3.02 mm of 'distance correction',[41] covers a visual field of more than 20× the size of the Maltese cross targets used in this experiment. It has been observed previously that the accommodation of a pre-presbyopic subject may be primarily modulated by the distance zone of multi-focal and dual-focus type CLs.[26–28]

In addition, the initial default destination for N–F accommodation is thought to be close to the subject's cycloplegic plane of focus.[48] The 'distance target' was located at a finite distance of 4 m, which may explain the relatively high accuracy of the distance AR, despite the increased DoF and reduction in the retinotopic defocus error signal in the MFCL. In any case, myopic defocus with the MFCL was minimal and well below 1D for all subjects during distance viewing. This supports the observation that children who are fitted with MFCL for myopia management purposes achieve acceptable levels of distance visual acuity with these lenses.[27,49,50] In response to the near target, the MFCL significantly reduced step response magnitudes and produced substantial amounts of hyperopic defocus compared with the SVCL.

Estimated hyperopic defocus when viewing the near target with the SVCL was 0.98D, on average. This compared well with previous reports for Maltese cross targets presented in unnatural monocular viewing conditions.[32,51] With the MFCL, which had an add-power of +2.50D, estimated hyperopic defocus increased by 0.91D. The smaller magnitude steps (Figure 3b) and moderately increased hyperopic defocus at near (Figure 6) suggest that accommodation control is not primarily driven by one of the two power zones of the MFCL. Instead, the distance and near transition zones of the MFCLs have been demonstrated to primarily dictate the retinal image quality achieved through MFCLs.[52] Gifford et al.[53] reported reduced ARs with a range of different MFCL designs, except for the CooperVision MiSight® lens (missight.com), which is a dual-focus CL. This suggests that the progression zone, which is a feature of MFCLs but not of the MiSight lens, might be key to generating the defocus error signal used for accommodation control.

Interestingly, a dual-focus lens, without an intermediate progression zone, yielded long-term treatment effects similar to MFCL with progressive zones used for myopia control therapy.[54] A confounding factor may be that, similar to this study, experiments which investigated various aspects of ocular accommodation or retinal image quality were frequently performed on pre-presbyopic adults, whereas clinical myopia control studies involve children. Some evidence suggests that accommodation control in children relies on a contrast control mechanism similar to that described for adults and uses medium spatial frequencies as the main driver of the response.[55] However, more work is required to understand fully how changes in retinal image quality, induced by multi-focal optics, affect the accommodation dynamics in children.

It should be noted that these discussions are based on measurements of focus at the central retina, since the targets in this study had an angular subtense of 1.98°. Considering just the central retina is, however, an oversimplification. Away from the fovea, the visual acuity of the eye declines sharply in accordance with the density of the cone photoreceptors.[56] However, there is evidence to suggest that the peripheral retina has the potential to influence the AR.[57–61] Further experimentation needs to be done to fully understand the role of the periphery in the accommodation step response, and in the mechanisms causing myopia.

In addition, chromatic aberration plays a role in accommodation,[62–66] and the role of wavelength was not explored in this experiment. The Maltese cross target was a black cross on an illuminated background, with the light containing a broad band of wavelengths. Although the effect of MFCLs specifically on chromatic aberrations has not been reported, it is likely to impact the chromatic profile compared to a SVCL, as MFCLs do affect monochromatic aberrations.[67–71]

Undoubtedly, the pupil diameter of the subjects will have an influence on the aberrations experienced though distance-centre MFCLs.[68,69] It will affect how much dioptric power of the progressive and near areas of the MFCL are utilised when subjects observed the target, which in turn will affect the DoF.[68] In this experiment, the pupil size was not controlled, to try and simulate natural viewing conditions whenever possible. As a minimum pupil diameter of 2.9 mm is required to obtain an accurate measurement using the Shin-Nippon SRW-5000[38] and DoF increases due to pupil diameter only when it is ≤2 mm,[72–75] one can conclude that an increased DoF was not induced by a small pupil diameter at any point in this experiment.

Pupil diameters were measured when viewing the distance target and ranged between 4 and 6.5 mm. The centre distance zone of the Biofinity MF CL has an outer diameter of 3.02 mm and the near zone starts at 4.50 mm,[41] with the intermediate zone in between. When viewing the distance target, all subjects will have experienced more visual cues than just those through the distance zone of the CL; however, the amount of intermediate and near zone cues available will have varied between subjects.

The experimental set-up aimed to be as close to real-life viewing as possible, using targets in free space rather than in a Badal lens system. The room lights were dimmed to maintain the minimum pupil diameter needed for accurate measurement but bright enough to allow both retinotopic and spatiotopic cues. There were, however, aspects of the set-up that resulted in the predominance of retinotopic over spatiotopic cues. For example, when subjects had their head on the chin rest, the target was the only object in view, so there were no real distance cues available. The targets were also size matched, and viewing was monocular, resulting in reduced information about target distance. The brightness of the targets was matched, but this did mean that because the near target was closer, its contrast was reduced in comparison to the distance target. Thus, the predominant cues available to the accommodation controller during the experiment as well as the aberrations mentioned above were contrast and defocus.

Approximately one fifth of responses were not recognised as correct steps but instead were solely composed of slow drift (SVCL: 11.9 ± 18.1%; MFCL: 19.2 ± 15.7%) or null steps (SV: 4.5 ± 6.7%; MFCL: 3.2 ± 3.9%). The presence of the MFCL did not influence these 'no step' responses, including on the type of slow drift, which was mainly in the correct direction. Figure 8 shows examples of a null step and a response that included slow drift in the correct direction, rather than a correct step.

Approximately one third of steps were followed by slow drift, reflective of an initial response towards the destination target vergence, which was further refined. This is expected since it is understood that the accommodation controller initially uses low spatial frequency information within a target to initiate a step response, which is then further refined using high spatial frequency information, which becomes increasingly available as the target becomes less blurred.[76–79] The vast majority of slow drift was in the correct direction, as shown by the example trace in Figure 8. This was not influenced by CL type, again suggesting that this is a normal AR as opposed to a feature of MFCL viewing. Figure 8 shows example traces of no step response, a response with slow drift in the correct direction instead of a correct step and a correct step followed by slow drift in the correct direction. The stimulus is shown, which changes at time point 0 s within this figure.

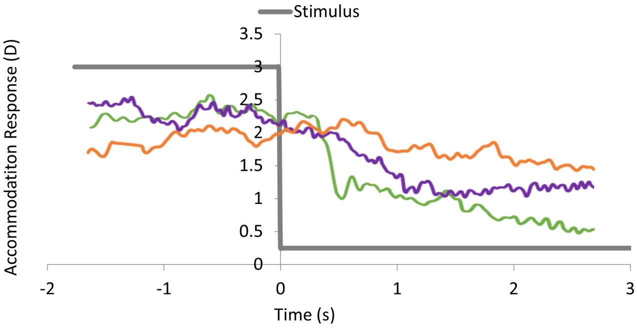

FIGURE 8 Example accommodation response traces demonstrating no step response (orange), a response slowly drifting in the correct direction (purple) and a step response followed by drift in the correct direction (green).

Refractive group differences

All step response parameters assessed in this study were similar between myopic and emmetropic subjects. Some previous investigations of accommodation to abrupt, stepwise changes in stimulus vergence have identified differences in myopes, while others have not. Late onset myopes demonstrated longer latencies and made less step responses in the correct direction than early onset myopes.[31] Additionally, late onset myopes had longer step durations after sustained near work.[32] However, in general, step direction did not differ between subject groups or experimental conditions.[32,35] Peak velocities were significantly faster when making larger steps for emmetropic subjects looking at higher spatial frequency (SF) targets, with no difference found between the high- and low-SF targets in the myopes.[34] In other research, myopes had shorter latencies than emmetropes,[33] or no difference was found.[31,34,35] Emmetropes were reported to have longer step durations for higher SF versus lower SF targets, with no difference found in the myopes between the high- or low-SF targets.[34]

Strang et al.[34] investigated refractive group differences to accommodation steps of various sizes and targets with different SF profiles. They reported that myopes showed a reduced ability to produce consistent responses to small changes in defocus (1D step change), whereas no differences were found between refractive groups for larger (3D) step stimuli. While removing low and high SFs from the target reduced the observer's ability to produce accurate ARs, even to large steps, both refractive groups were affected equally. In this study, some attenuation, particularly of the high SF contained in the stimulus, would be expected, due to the optical transfer function of the MFCL. It is likely that this was overcome by the availability of an extensive set of cues, combined with a large (2.75D) change in stimulus vergence.

There is conflicting evidence regarding the accuracy of the AR to a stationary target in myopes compared with emmetropes, where younger myopes have been reported to have larger lags of accommodation than their emmetropic counterparts.[4–9] Conversely, no difference between refractive groups has also been reported,[10–12] which is in accordance with the results of this experiment.

Retinal defocus

Optical interventions, thought to provide a protective effect against myopia progression, aim to incorporate myopic defocus into the retinal image shell. The MFCL used in this study was likely to produce a combination of some peripheral defocus,[52,71] which may be myopic depending on the patient's retinal shape, and central myopic defocus along the visual axis due to the simultaneous lens design. To approximate the amount of defocus along the visual axis with the MFCL, the measured accommodative response was adjusted by the power of the MFCL near zone, and the estimated group mean central retinal defocus values along the visual axis are illustrated in Figure 9. Both the SVCL and the distance zone of the MFCL seem to produce very little retinal defocus when viewing the distance target. A lead of accommodation, producing a small amount of myopic defocus, is frequently seen for targets close to optical infinity.[1,5,80] In this experiment, where the stimulus vergence was −0.25D, the response was similar to that reported previously.[81–85] When viewing the distance target, a negligible amount of hyperopic defocus was estimated from the distance zone of the MFCL, while the near zone estimated the presence of myopic defocus, approximately equivalent to the +2.50D near addition of the MFCL.

Viewing the near target produced hyperopic retinal defocus through the distance zone of the MFCL. The near zone of the MFCL was estimated to produce myopic defocus, but this was reduced by approximately 75% at near when compared to distance viewing.

It should be noted that the estimates of dioptric retinal defocus are an over-simplification because they do not fully account for the aberrations produced by the MFCLs. The Shin-Nippon autorefractor measurement does not measure aberrations directly but uses the size of the measurement circle to obtain a refraction reading and this will be influenced by the aberrations of the eye. First, this could influence the accuracy of the refraction measurements. Labhishetty et al.[86] recently reported increased hyperopic defocus measurements with autorefraction compared to aberrometry, with the largest accommodative errors reported through autorefraction. Conversely, there was no significant difference in defocus measured by aberrometry and autorefraction in other studies.[87–90] Second, in the current experiment the refraction measurement was taken from the eye without a contact lens in place, and calculations were used to estimate the location of the focal points once they passed through the MFCL D and N sections. This does not account for the aberrations altered by the MFCL.[67–71] Aberrations could provide alternative or additional cues to the dioptric retinal defocus discussed above, both for the accommodation controller and in regard to eye growth and the development of refractive error.[71,91]

It is generally accepted that emmetropisation is driven by retinal defocus, but there is uncertainty regarding the amount of defocus required to reduce myopic progression.[92] Most animal studies show that even small amounts of defocus can result in axial length changes.[13,93–100] A recent study[101] demonstrated a significant reduction in myopia progression in subjects treated with MFCLs with a +2.50D add power but no significant reduction for those with a +1.50D add. This would suggest a dose-dependent response to blur through different optical designs. Cheng et al.[30] reported a correlation between the reduced AR and increased myopia progression in MFCL wearers, also agreeing that the optics associated with reduced

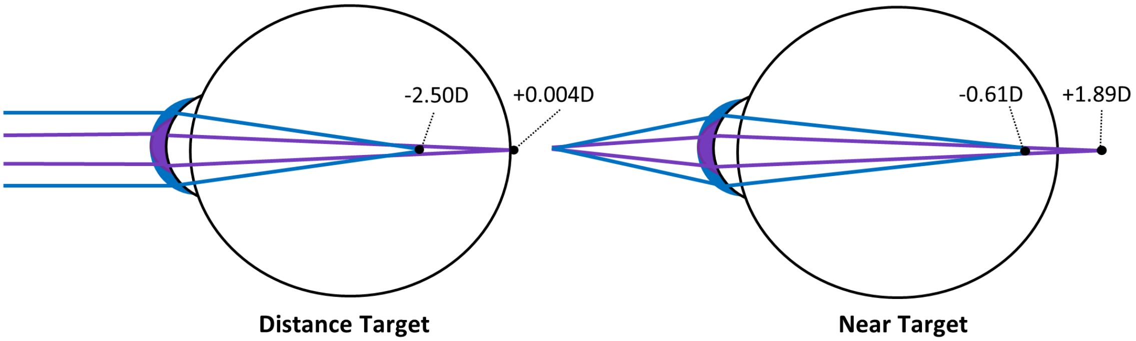

FIGURE 9 Schematic representation of group mean estimated central dioptric defocus along the visual axis with the multifocal contact lens (MFCL) for the distance and near targets. The purple and blue rays represent the distance and near zones, respectively. Note that substantially more myopic defocus is estimated when viewing the distance target.

accommodation through the MFCLs could have a role in myopia management.

On average, MFCL interventions achieved a change of only 0.15D/year compared to SVCLs, or 0.07 mm/year in the Bifocal Lenses in Nearsighted Kids (BLINK) study using a Biofinity centre distance lens,[101] and 0.22D/year or 0.09 mm with MiSight lenses,[102] both over 3 years. It could be speculated that the presence of simultaneous hyperopic and myopic defocus may reduce treatment efficiency, although chicks exposed to alternating hyperopic and myopic defocus appeared to manifest hyperopia.[103,104]

Pupil diameters during the present investigation were well above 3 mm and values are shown in Table 1. In addition to the increased aberrations and their optical effects on the point-spread function, larger pupils result in increased crosstalk between photoreceptors[105] and will further degrade retinal image quality and accommodative accuracy, while smaller pupils reduce the impact of oblique rays and aberrations.

The results of the present study approximate that MFCLs provide a greater amount of 'protective' myopic defocus during distance viewing. Further, a recent study[106] has shown that time spent outdoors is a primary factor for inhibiting axial length progression with MFCLs. From a practical perspective, therefore, clinicians may want to educate patients who wear MFCLs for myopia management about the benefits of spending time outdoors to maximise these aspects.

CONCLUSION

Pre-presbyopes do not appear to derive the defocus error required for accommodation control solely from the distance zone of the MFCL. This leads to inaccuracies in ocular accommodation during near tasks through MFCLs, which has been implicated in a reduced treatment response through these lenses.[30] A reduced performance to abruptly changing vergence stimuli was found, although this deterioration in dynamic performance was small and unlikely to have an impact on everyday visual tasks. Through MFCLs, the estimated dioptric defocus along the visual axis included myopic defocus irrespective of the stimulus vergence. This was largest when viewing a distant stimulus, supporting the hypothesis that outdoor locations provide a beneficial visual environment to reduce myopia progression.

AUTHOR CONTRIBUTIONS

Mubeen Mahmood: Conceptualization (supporting); data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (lead); writing – original draft (lead); writing – review and editing (equal). **Mhairi Day:** Conceptualization (lead); formal analysis (supporting); resources (lead); software (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (equal). **Dirk Seidel:** Conceptualization (supporting); resources (supporting); software (supporting); supervision (supporting); writing – original draft (supporting); writing – review and editing (equal). **Lorraine A. Cameron:** Conceptualization (supporting); writing – original draft (supporting).

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CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest for this article.

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