Visual Psychophysics and Physiological Optics

# Changes in Shape Discrimination Sensitivity Under Glare Conditions After Orthokeratology in Myopic Children: A Prospective Study

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**Purpose.** To investigate changes in shape discrimination under mesopic conditions with and without glare after orthokeratology in myopic children.

**Methods.** This prospective study included 79 eyes of 79 myopic children (ages: 8–16 years). Shape discrimination thresholds (SDTs) were measured using radial frequency patterns, with a radial frequency of 4 cycles/360°, a peak spatial frequency of 3 cycles per degree, a contrast of 20%, and a mean radius of 1.5 degrees. SDT under mesopic conditions with and without glare was measured before orthokeratology and again at 1 week and 1 month after orthokeratology. Changes in the SDTs and their relationships to baseline ocular parameters were analyzed.

**Results.** SDTs with glare decreased significantly at 1 week (−0.08 ± 0.15 log(arcsec), $P < 0.001$) and 1 month (−0.09 ± 0.15 log(arcsec), $P < 0.001$) after orthokeratology. SDTs without glare remained stable ($P = 0.81$ and $P = 1.00$, respectively). The difference between SDTs with and without glare also decreased significantly at 1 week (−0.10 ± 0.17 log(arcsec), $P < 0.001$) and at 1 month (−0.08 ± 0.18 log(arcsec), $P = 0.001$) after orthokeratology. Based on a multivariate analysis, the greater decrease in SDT with glare after 1 month of orthokeratology was associated with a higher baseline spherical equivalent refraction.

**Conclusions.** Orthokeratology resulted in improved shape discrimination in myopic children under mesopic conditions but only when measured in the presence of glare.

Keywords: orthokeratology, shape discrimination, visual performance, glare, radial frequency pattern

Orthokeratology lenses are specialty rigid contact lenses with a reverse geometry design on the posterior surface. When worn overnight, the orthokeratology lens reshapes the cornea, temporarily reducing the refractive error and improving the uncorrected visual acuity upon lens removal.[1,2] Numerous studies have shown that orthokeratology is an effective method for controlling myopia progression in children,[3–5] and it has become widely used in the treatment of myopia in Chinese school-age children.[6]

The corneal reshaping induced by myopic orthokeratology thins the central corneal epithelium and thickens the epithelium of the cornea adjacent to the reverse curve.[7,8] In doing so, it flattens the central cornea, steepens the midperipheral cornea,[9,10] and reduces the cornea sensitivity.[11] On the other hand, the corneal surface regularity index and surface asymmetry index can increase significantly after orthokeratology.[12–14] These irregular changes can lead to an increase in higher-order aberrations (HOAs)[15,16] and a decrease in contrast sensitivity.[17,18] For instance, by comparing the area under the contrast sensitivity function of myopic children, Liu et al.[19] found that orthokeratology decreased contrast sensitivity under both photopic and mesopic conditions. However, Chang and Cheng[20] reported that contrast sensitivity under mesopic conditions decreased at 1.5, 3, and 12 cycles/deg while there was no significant decrease in contrast sensitivity under photopic conditions.

In addition, a recent study investigated visual distortions (i.e., subjectively perceived shape distortion) associated with the irregularly altered corneal morphology after orthokeratology.[21] Biederman and Ju[22] and Elder[23] showed that shape perception helps with the recognition of objects in daily life, usually guided by the shape of object boundaries or contours. Moreover, the shape perception of objects can affect visually guided actions[24] and reading.[25] Using a radial frequency (RF) pattern, which is a classic shape recognition stimulus introduced by Wilkinson et al.,[26] we previously showed that corneal asymmetry increased without a significant reduction in shape discrimination in children after orthokeratology.[21] The lack of change in shape discrimination is not consistent with findings of decreased contrast sensitivity,[18,21] which may indicate that the effect of orthokeratology treatment on visual perception is task specific.

Notably, we previously evaluated the changes in shape discrimination sensitivity under mesopic conditions after the initiation of orthokeratology and found there was no significant change in shape discrimination sensitivity.[21] Mesopic conditions are not representative of everyday viewing. In clinical practice, similar to corneal refractive surgeries, patients with orthokeratology often have symptoms of glare and halos, both of which can affect visual performance.[27,28] Corneal surface irregularities can also lead to an increase in glare.[29] Therefore, in the study described here, we asked whether or not orthokeratology treatment affects the shape discrimination sensitivity of children in mesopic conditions with glare. To address this question, we designed a prospective study to evaluate and compare the mesopic shape discrimination threshold (SDT), with and without glare, in children before and at 1 week and 1 month after orthokeratology.

## Methods

### Participants

Ninety myopic children scheduled to undergo orthokeratology were enrolled in this prospective study. The inclusion criteria were age between 8 and 16 years, spherical refractive error between −1.00 and −5.00 diopters (D), astigmatism of less than or equal to −1.50 D, and a best-corrected visual acuity of 0 logMAR or better. Exclusion criteria were based on the presence of active ophthalmic disease, strabismus, and a history of ocular surgery. Only the right eye of each eligible participant was included. Eleven children were excluded because their uncorrected visual acuity was worse than 0.1 logMAR or they experienced severe lens decentration on corneal topography maps (greater than 1.0 mm) recorded 1 week or 1 month after orthokeratology treatment. In the end, 79 children (mean ± SD age 11.1 ± 1.9 years; 28 males, Table 1) completed this study. The study protocol was approved by the ethics committee of the Eye Hospital of Wenzhou Medical University and adhered to the tenets of the Declaration of Helsinki. All participants and their parents signed consent forms after the purpose, procedures, and possible risks of the study were explained to them.

### Apparatus

The experimental stimuli were generated by MATLAB (version 2012a; MathWorks, Natick, MA, USA) and Psychotoolbox[30] on a Windows 7–based computer. All stimuli were displayed on a gamma-corrected light-emitting diode monitor (BL2710PT; BenQ Corp., Suzhou, China). The screen resolution was 2560 × 1440 pixels, the refresh rate was 60 Hz, and the mean luminance was 10 cd/m$^2$.

**Table 1.** Demographics and Baseline Data of the Participating Children ($n$ = 79)

| Parameter | Value |
|---|---|
| Age, y | 11.1 ± 1.9 (8–16) |
| Sex (male), $n$ (%) | 28 (35.4) |
| Spherical equivalent refraction, D | −3.23 ± 1.03 (−1.25 to −5.50) |
| Mesopic pupil size, mm | 6.5 ± 0.7 (4.2–8.0) |
| Best-corrected visual acuity, logMAR | −0.06 ± 0.04 (−0.08 to 0) |

Values are presented as mean ± SD (range) unless otherwise indicated.

### Procedures

The orthokeratology lenses had a four-zone reverse geometry (Euclid Systems Corporation, Herndon, VA, USA) and were composed of oprifocon A (Boston Equalens II, Boston Materials, Billerica, MA, USA) with an oxygen permeability (DK) of 90 × $10^{-11}$ (cm$^2$/s)(mL $O_2$/mL*mm Hg). The overall diameter of each lens was 10.2 to 11.0 mm, with an optic zone diameter of 6.2 mm. Lens fitting was performed according to the manufacturer's fitting guidelines. Well-fitting lenses were centered on the cornea with approximately 1 mm of movement during a blink and had a classical bullseye fluorescein pattern. After lens dispensing, the participants were advised to wear the lens for 8 to 10 hours per night.

Before orthokeratology treatment, we measured each participant's noncycloplegic subjective refraction, uncorrected visual acuity, best-corrected visual acuity, corneal topography, mesopic pupil size, and SDT. Participants were routinely followed up according to the clinical requirements of orthokeratology. At 1 week and 1 month after orthokeratology treatment, we remeasured uncorrected visual acuity, noncycloplegic subjective refraction (only if the uncorrected visual acuity was worse than 0.1 logMAR), corneal topography, and SDT.

Corneal topography was measured using the Medmont E300 corneal topographer (Medmont International Pty. Ltd., Victoria, Australia). Keratometric values corresponding to the two principal meridians (flattest and steepest) were recorded. Anterior ocular segments and lens fitting were examined using a slit-lamp microscope. The posterior ocular segment was examined by ophthalmoscopy and pupil size was measured with the Vip-200 pupillometer (NeurOptics, Irvine, CA, USA).

### Shape Discrimination Threshold Determination

As we previously reported,[21,31] SDT was measured with a custom-built RF pattern program that projected a circular contour with a cross-sectional luminance profile defined by a radial fourth derivative of a Gaussian distribution. The contrast of the RF pattern was 20%, with an RF of 4 cycles/360°, peak spatial frequency of 3.0 cycles per degree, and a mean radius of 1.5 degrees. The glare was induced as described in previous studies.[31–33] Specifically, the glare source consisted of a 10-watt light-emitting diode located 8° to the right of the stimulus at a viewing distance of 1 m (Fig. 1A). Before orthokeratology, the SDT was measured with refractive errors corrected using trial lenses. Measurements of SDT after commencement of orthokeratology were made without refractive correction.

The SDT was determined by a two-interval forced-choice task (Fig. 1B). The order in each of the two patterns shown in each trial was randomized. One was an undeformed RF pattern (a perfect circle), and the other was a deformed RF pattern. Each stimulus interval was 500 ms, separated by a 500-ms interstimulus interval. Participants were asked to indicate which interval contained the deformed RF pattern and respond using a keyboard. The threshold of RF pattern amplitude was determined by a two-down, one-up staircase algorithm. After eight reversals, the test ended, and the mean of the last six reversals was recorded as the SDT value in logarithmic scale. Mesopic SDT was assessed with and without glare. The room illuminance during the test was about 0.4 lumen/m$^2$. Under glare conditions, the glare and stimuli were displayed simultaneously. Fifteen minutes of dark adaptation preceded the start of testing, and 5-minute breaks were provided between trials.

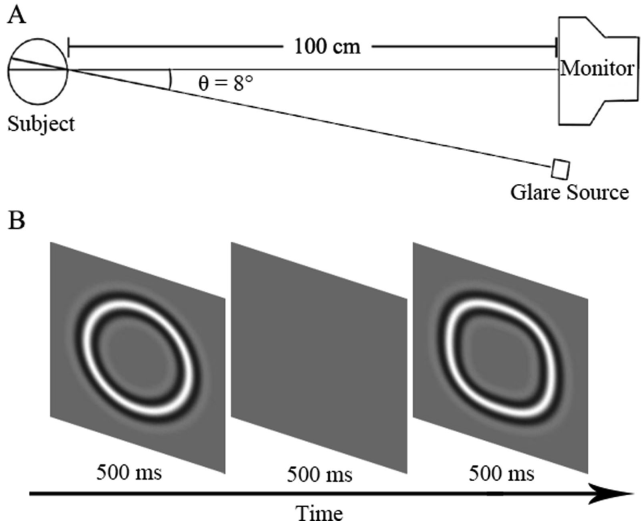


**Figure 1.** (**A**) Schematic diagram of the experimental apparatus. (**B**) The shape discrimination threshold was measured using a two-interval forced-choice task. The participant was asked to indicate which stimulus interval contained the deformed radial frequency pattern. The radial frequency of the pattern was 4 cycles/360°, the peak spatial frequency was 3.0 cycles/deg, the contrast was 20%, and the average radius was 1.5 degrees. The duration of each stimulus interval and the interstimulus interval was 500 ms.

The participants were first asked to perform the SDT test three times without glare. Following that, the test was performed three times with glare. Means were derived from each of the sets of three SDT measurements, corresponding to the two conditions. The difference between SDT with glare and SDT without glare indicated the effect of glare on SDT.

### Sample Size Calculation

The primary study outcome was the change of SDT measured under glare conditions 1 month after orthokeratology. Similar to other studies,[34,35] we conducted a pilot study with 15 children to determine the appropriate sample size. In that test, the baseline SDT with glare was 1.72 ± 0.12 log(arcsec). The SDT with glare changed to 1.64 ± 0.10 log(arcsec) 1 month after orthokeratology. To achieve a power of 90% with a significance level of 0.05, at least 28 participants were required. Considering that the sample size calculation was based on a small sample and that other factors could affect data collection, such as irregular overnight orthokeratology lens wear by the children, loss to follow-up, poor uncorrected visual acuity, and/or poor lens fitting, we ultimately recruited 90 children for this study.

### Statistical Analysis

Statistical analyses were performed with SPSS (version 25.0; IBM Corp., Armonk, NY, USA) and OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA). The Shapiro–Wilk test was conducted to analyze the normality of data distribution. Changes in the SDTs and corneal curvature produced between baseline and each follow-up visit were compared by repeated-measures ANOVA. Friedman tests were used to examine the changes in uncorrected visual acuity. Post hoc tests were performed with a Bonferroni correction. A Deming regression was used to evaluate the correlation between posttreatment and baseline SDTs. Univariate and multivariate linear regression analyses were performed to determine the associations between the change in SDT and the baseline ocular parameters. Factors with significant associations in the univariate analysis were included in the multivariate regression analysis. $P$ values of less than 0.05 were considered statistically significant.

## Results

### Corneal Curvature and Uncorrected Visual Acuity After Orthokeratology

Compared to the baseline corneal curvature profiles, both flat and steep meridians were significantly flatter (i.e., corneal powers reduced) after both 1 week and 1 month of orthokeratology (all $P < 0.001$, Table 2). The children's uncorrected visual acuity improved significantly from 0.82 ± 0.29 logMAR at baseline to −0.008 ± 0.071 logMAR at 1 week ($P < 0.001$) and −0.011 ± 0.073 logMAR at 1 month ($P < 0.001$). There was no significant difference between the uncorrected visual acuities recorded at 1 week and 1 month ($P = 0.87$).

### Shape Discrimination Threshold After Orthokeratology

SDT with and without glare and the difference between SDT with and without glare at baseline and both at 1 week and 1 month after orthokeratology were determined (Table 2 and Fig. 2). Repeated-measures ANOVA showed that the SDTs without glare were not significantly changed at either 1 week or 1 month of orthokeratology compared to the baseline SDT ($P > 0.80$ for both comparisons). However, at the same time, SDTs with glare were significantly reduced ($P < 0.001$). Bonferroni post hoc test showed that SDT with glare was decreased significantly at 1 week (−0.08 ± 0.15 log(arcsec), $P < 0.001$) and at 1 month (−0.09 ± 0.15 log(arcsec), $P < 0.001$) after orthokeratology.

To determine the effect of glare on SDT, we also calculated the differences between SDT with and without glare. If

**Table 2.** Uncorrected Visual Acuity, Corneal Curvature, and Shape Discrimination Threshold Before and After Orthokeratology

| Parameters | Baseline, Mean ± SD | 1 Week, Mean ± SD | 1 Month, Mean ± SD | $P$ Value |
|---|---|---|---|---|
| Uncorrected visual acuity, logMAR | 0.82 ± 0.29 | −0.008 ± 0.071 | −0.011 ± 0.073 | <0.001* |
| Flat keratometric value, D | 42.87 ± 1.38 | 41.17 ± 1.52 | 40.88 ± 1.53 | <0.001† |
| Steep keratometric value, D | 44.02 ± 1.55 | 42.67 ± 1.73 | 42.55 ± 1.80 | <0.001† |
| SDT with glare, log(arcsec) | 1.70 ± 0.13 | 1.62 ± 0.13 | 1.61 ± 0.14 | <0.001† |
| SDT without glare, log(arcsec) | 1.42 ± 0.10 | 1.44 ± 0.11 | 1.41 ± 0.11 | 0.13† |
| Difference between SDT with and without glare, log(arcsec) | 0.28 ± 0.15 | 0.18 ± 0.13 | 0.20 ± 0.15 | <0.001† |

* Friedman test.
† Repeated-measures ANOVA.

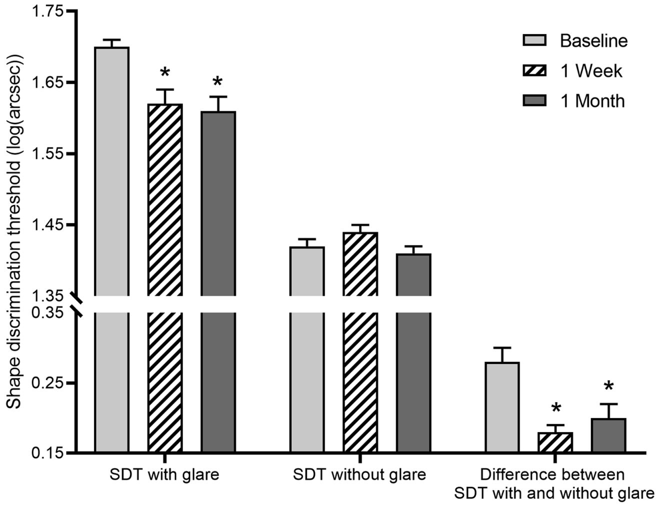


**Figure 2.** SDT with glare, SDT without glare, and the difference between them. Data are shown as means ± standard error of the mean. *$P < 0.05$ compared to the baseline value, post hoc test with Bonferroni correction after repeated-measures ANOVA.

there is a change in glare after orthokeratology, we expect there to be a change in the difference between SDT with and without glare. Indeed, the difference between SDT with and without glare decreased significantly at 1 week (−0.10 ± 0.17 log(arcsec), $P < 0.001$) and at 1 month (−0.08 ± 0.18 log(arcsec), $P = 0.001$) after orthokeratology.

The mean SDT with glare and the difference between SDTs with and without glare decreased after orthokeratology. To further observe the pattern of the change for individual participants, we performed a Deming regression analysis on the measurements at 1 month and baseline. For SDT with glare, the Deming regression $R^2$ was 0.125 with a slope of 1.10 (95% confidence interval [CI], 0.30 to 1.89), and the intercept was −0.25 (95% CI, −1.61 to 1.10) log(arcsec) (Fig. 3A). For the difference between SDT with and without glare, the Deming regression $R^2$ was 0.085 with a slope of 0.97 (95% CI, 0.07 to 1.87), and the intercept was −0.07 (95% CI, −0.32 to 0.18) log(arcsec) (Fig. 3B).

## Univariate and Multivariate Associations With the Changes in SDTs

To explore factors associated with orthokeratology-induced changes in SDT with glare and the difference between SDT with and without glare, we analyzed the correlations with potentially relevant ocular parameters. According to univariate and multivariate analyses, the change in SDT with glare after 1 month of orthokeratology was negatively associated with the baseline spherical equivalent refraction ($\beta$ = −0.03, $P = 0.048$, Table 3, Fig. 4) but not with the baseline mesopic pupil size or cornea curvature (both $P \geq 0.14$).

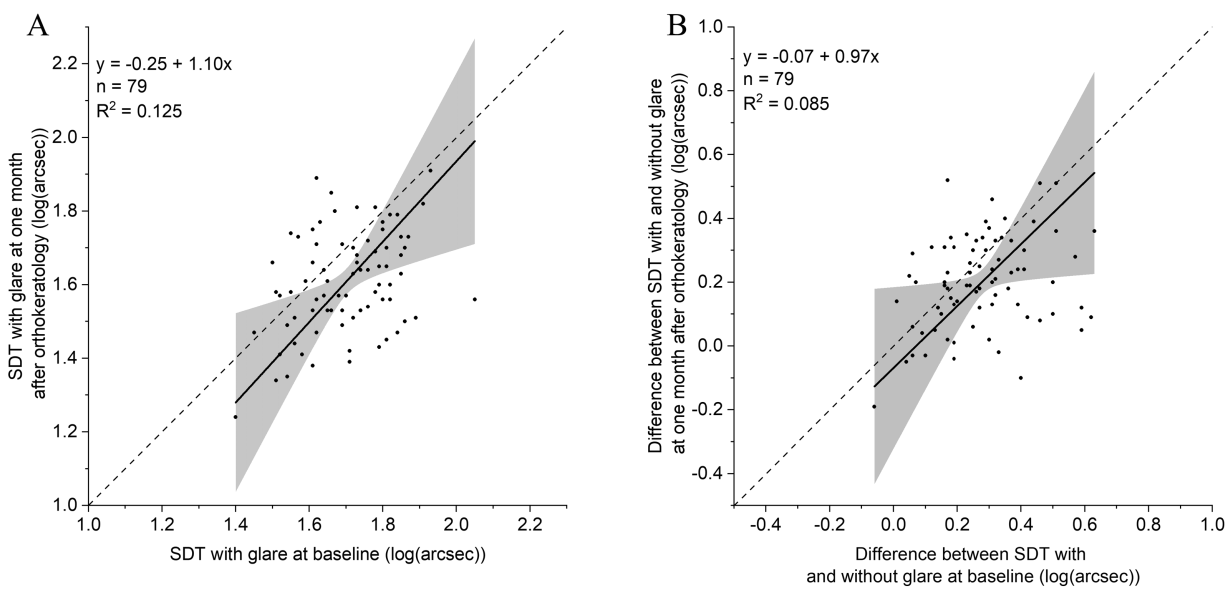


**Figure 3.** (**A**) Deming regression of SDT between baseline and 1 month after orthokeratology recorded under the glare conditions. The solid line displays the Deming regression line (slope = 1.10 [95% CI, 0.30 to 1.89], intercept = −0.25 [95% CI, −1.61 to 1.10] log(arcsec), $R^2 = 0.125$, and $P = 0.008$). The dashed line represents the Y = X line. (**B**) Deming regression analysis of the SDT difference with and without glare at 1 month after orthokeratology and at baseline. The solid line displays the Deming regression line (slope = 0.97 [95% CI, 0.07 to 1.87], intercept = −0.07 [95% CI, −0.32 to 0.18] log(arcsec), $R^2 = 0.085$, and $P = 0.03$). The dashed line represents the Y = X line.

**Table 3.** Univariate and Multivariate Analysis of Changes in SDT With Glare After 1 Month of Orthokeratology

| | Univariate Associations | | Multivariate Associations | |
|---|---|---|---|---|
| **Baseline Parameter** | **$\beta$ (95% CI)** | ***P* Value** | **$\beta$ (95% CI)** | ***P* Value** |
| Spherical equivalent refraction | −0.03 (−0.07 to 0.00) | 0.048 | −0.03 (−0.07 to 0) | 0.048 |
| Mesopic pupil size | 0.02 (−0.03 to 0.07) | 0.47 | | |
| Flat keratometric value | −0.02 (−0.04 to 0.01) | 0.14 | | |
| Steep keratometric value | −0.01 (−0.03 to 0.01) | 0.28 | | |

**Table 4.** Univariate and Multivariate Association With the Change in Difference Between SDT With and Without Glare After 1 Month of Orthokeratology

| | Univariate Associations | | Multivariate Associations | |
|---|---|---|---|---|
| **Baseline Parameter** | **$\beta$ (95% CI)** | ***P* Value** | **$\beta$ (95% CI)** | ***P* Value** |
| Spherical equivalent refraction | −0.03 (−0.07 to 0.00) | 0.09 | | |
| Mesopic pupil size | 0.01 (−0.04 to 0.07) | 0.66 | | |
| Flat keratometric value | −0.01 (−0.04 to 0.02) | 0.61 | | |
| Steep keratometric value | 0.00 (−0.03 to 0.02) | 0.88 | | |

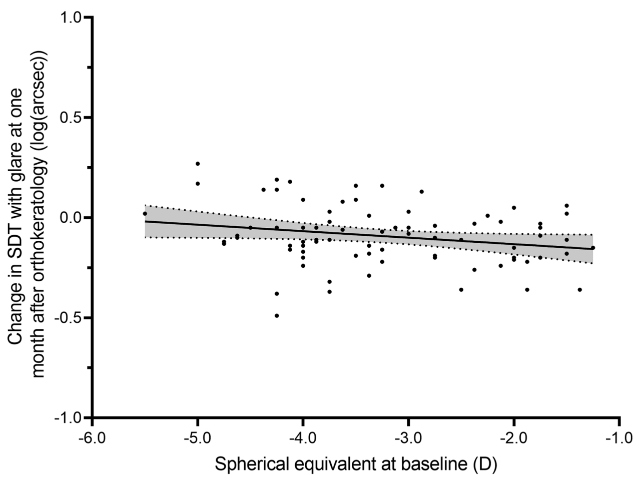


**Figure 4.** Linear regression analysis scatterplot of the change in SDT with glare and baseline spherical equivalent refraction at 1 month after orthokeratology.

The change in the difference between SDT with and without glare after 1 month of orthokeratology was not significantly correlated with baseline spherical equivalent refraction, mesopic pupil size, or corneal curvature (all $P \geq 0.09$, Table 4).

## Discussion

In this study, we determined the effect of orthokeratology treatment on shape discrimination sensitivity in myopic children under mesopic conditions with and without glare. Our results showed that orthokeratology treatment for up to 1 month improved the mesopic shape discrimination sensitivity with glare; however, it did not affect the sensitivity without glare. The change in SDT with glare was negatively associated with baseline spherical equivalent refraction.

Previous studies have reported an increase in glare-related symptoms in patients after orthokeratology treatment.[27,28] Adults using orthokeratology also experienced more severe symptoms of glare when compared with adults using spectacles and contact lenses.[36] Other studies have found an increase in objective intraocular scattering in patients after orthokeratology.[19,37] However, the objective scattering index after orthokeratology was still very small, with an average value of less than 1, which is within the normal range.[38] Lorente-Velazuez et al.[39,40] found that straylight decreased significantly after 1 month of orthokeratology treatment. This was consistent with our findings that the difference between SDT with and without glare after orthokeratology was lower than the difference at baseline.

Numerous studies have reported a decrease in contrast sensitivity under nonglare conditions after orthokeratology.[41,42] However, the significant decrease in contrast sensitivity after orthokeratology was not robustly related to satisfaction with visual outcomes.[43] Our results show that there was no significant difference in the SDT of myopic children under mesopic conditions without glare before or after orthokeratology, which is consistent with the findings of Xia et al.[21] Under mesopic conditions with glare, previous studies found that patients' contrast sensitivity decreased after orthokeratology.[19,44] However, there are not many studies involving daily task-related visual performance under glare conditions after orthokeratology. Surprisingly, our results show that SDT with glare decreased significantly in myopic children at 1 week and 1 month after orthokeratology, indicating that shape discrimination sensitivity with glare improved. Our study, together with that of Xia et al.,[21] shows that orthokeratology treatment does not reduce shape discrimination sensitivity under mesopic conditions without glare, and paradoxically, SDT improves under mesopic glare conditions.

RF patterns are processed in human occipital lobe V4 and involve local orientation and curvature extraction in V1 and V2.[45,46] The RF pattern used in this study was RF4, a lower RF pattern that is thought to be detected globally.[47] Wilkinson et al.[26] reported that a reduction in contrast from 100% to 12.5% did not affect the SDT of RF4. The RF4 contrast in this study was 20%, which was still at a relatively high level. So, even if the contrast sensitivity decreased after orthokeratology, SDT might not have been affected.

Recent studies show that refractive correction with minus power lenses can lead to a slight increase in straylight.[48,49] In addition, the spectacle lenses themselves could also cause a slight additional light scatter.[50] After orthokeratology, children do not need to wear spectacles in the daytime. This would avoid any light scatter caused by the lenses and thereby improve shape discrimination sensitivity under glare conditions. In the current study, we measured each child's shape discrimination sensitivity before orthokeratology with their refractive errors corrected by spectacle lenses and then again, but without spectacles, after orthokeratology. We note that the change of retinal image magnification caused by spectacle lenses might also affect the sensitivity of shape discrimination.

There are two reasons for choosing spectacle lens correction rather than contact lens correction in the baseline measurements. First, spectacle lenses are the most common form of correction for myopic children before orthokeratology. Baseline measurements with spectacle lenses thus enabled us to compare the glare effect on the children's daily life before and after orthokeratology. Second, Rozema et al.[51] and Allen et al.[52] reported that wearing contact lenses could cause more straylight than wearing spectacles. This, in turn, might have affected our measurements of shape discrimination sensitivity under glare conditions. Thus, it will be important to test the changes of shape discrimination sensitivity of myopic children with the same corrections (i.e., spectacles or contact lenses). Such tests could enable us to clarify the effect of orthokeratology on the visual processing of shape discrimination.

We did not find a correlation between mesopic pupil size and SDT and/or SDT changes after orthokeratology. We measured mesopic pupil size only at baseline. We did not record it after orthokeratology, nor did we record the change in pupil size due to glare. This may have affected the results of pupil size and SDT correlation analysis, which is a limitation of this study. One important topic to explore is whether or not glare-induced pupillary constriction can cause a decrease in SDT with glare after orthokeratology treatment. Previously, Pauné et al.[53] and Tan et al.[54] reported that there was no significant change in either photopic or mesopic pupil size after orthokeratology. Therefore, for the same participants, in the same test settings, we expect glare-induced pupillary constriction to be consistent before and after orthokeratology. Pupillary constriction would result in a decrease in HOAs.[55] However, the reduction of HOAs caused by the same degree of pupillary constriction could be different before and after orthokeratology. To illustrate, Joslin et al.[56] measured the HOAs of 3-mm and 6-mm pupil sizes before and 1 month after orthokeratology. Pupil size–related differences in HOAs were significantly greater after orthokeratology than before treatment, with HOAs decreasing with pupil size. Although pupil size was not measured in the current study, it is likely that glare-induced pupillary constriction would have decreased HOAs, in turn positively affecting shape discrimination.

Our study shows that children with less myopia at baseline have a greater decrease in SDT with glare after orthokeratology than those with more myopia. Eyes with more myopia have greater corneal reshaping after orthokeratology than do eyes with less myopia,[7,57] and a larger amount of reshaping may have negative effects on SDT with glare. Moreover, the treatment zones in eyes with less myopia are larger and are more likely to cover the pupil and thus less prone to glare problems.

In conclusion, our results suggest that compared to spectacle lens wear, conventional orthokeratology does not adversely affect visual performance under mesopic conditions. After orthokeratology, the shape discrimination sensitivity improved in myopic children under mesopic conditions with glare, while shape discrimination sensitivity remained stable under mesopic conditions without glare.

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