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A novel tool for quantitative measurement of distortion in keratoconus

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1   **A novel tool for quantitative measurement of distortion in keratoconus**

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11

12   **Abstract**

13   **Background:** Keratoconus is associated with thinning and anterior protrusion of the cornea resulting

14   in the symptoms of blurry and distorted vision. The commonly used clinical vision tests such as visual

15   acuity and contrast sensitivity may not reflect the symptoms experienced in keratoconus and there are

16   no quantitative tools to measure visual distortion. In this study, we used a quantitative test based on

17   vernier alignment and field matching techniques to quantify visual distortion in keratoconus and

18   assess its relation to corneal structural changes.

19   **Methods:** A total of 50 participants (25 keratoconus and 25 visually normal) completed the

20   experiment where they aligned supra-threshold white target circles in opposite field in reference to

21   guide lines and circles to complete a square structure. The task was repeated five times and the global

22   distortion index (GDI) and global uncertainty index (GUI) were calculated as the mean and standard

23   deviation respectively of local perceived misalignment of target circles over five trials.

24   **Results:** Both GDI and GUI were higher in participants with keratoconus compared to controls ($p <$

25   0.01). Both parameters correlated with the best corrected visual acuity, maximum corneal curvature

26   (K_{max}), topographical keratoconus classification (TKC) and central corneal thickness (CCT).

27   **Conclusion:** Our findings show that the quantitative measure of distortion could be a useful tool for

28   behavioural assessment of progressive keratoconus.

Introduction

Keratoconus is a progressive corneal condition characterised by anterior protrusion and thinning of the cornea. The aetiology of the condition is multifactorial with recent studies suggesting a role of inflammatory mechanisms.(1, 2) The estimated prevalence of keratoconus is reported to be 1 in 84 (3) to 1 in 375 (4) in young adults. The condition has a genetic heterogeneity and involves both autosomal dominant and autosomal recessive patterns.(5) The corneal structural changes lead to irregular astigmatism and myopia with the symptoms of blurry vision, increased sensitivity to glare, and distorted vision due to higher order aberrations.(6-8) The symptoms begin in adolescence or early adulthood and usually slowly progresses until mid-adulthood.(8)

The commonly assessed structural measurements in keratoconus include corneal curvature, corneal topography, and corneal thickness using keratometer, corneal topographer, and ocular coherence tomogram (OCT) respectively. Visual acuity is the most commonly measured visual function outcome in the clinical setup. However, visual acuity is not a good predictor of symptoms experienced in keratoconus and vision related quality of life is reduced even in early stages of the disorder while good visual acuity may be maintained. (9-12) Contrast sensitivity meanwhile correlates both with higher order aberration (7, 13) and topographic indices (14). However, clinically available contrast sensitivity charts may not be appropriate for the evaluation of moderate to advanced keratoconus. (15) Hence there is a lack of a perceptual visual measure that reflects symptoms experienced in keratoconus. Different parameters indicate keratoconus progression, and therefore need for intervention with methods such as collagen cross-linking. These include an increase in maximum corneal curvature by 1 D over a year (16), increase in astigmatism by 1 - 3 DC over 6 months, and reduction in central corneal thickness by 5% over 6 months (17). Previous studies have demonstrated variable correlation of best-corrected visual acuity with these parameters, with contrast sensitivity again showing a better correlation.(18, 19) However, monitoring clinical progression requires specialist imaging equipment, and therefore regular visits to an eye care professional are required. Recently a new scoring system that includes clinical measures and the patient characteristics such as patient reported quality of vision, the Dutch Crosslinking for Keratoconus Score, is reported to be

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57 better at predicting when medical intervention may be needed.(20) A reliable perceptual

58 measurement that better reflects patient's visual status may further aid development of such scoring

59 system. Such a measure could also potentially be used as a home-based test.

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61 While visual distortion is one of the most common symptoms in keratoconus, there are currently

62 limited methods to quantify such distortion and none as far as we are aware specifically designed for

63 keratoconus. There have been approaches to quantify distortion using hyperacuity tasks in different

64 ocular conditions. (21-24)   Hyperacuity refers to the visual system's ability to perform spatial tasks

65 beyond the eye's classical resolution limit with thresholds as low as 3 to 6 secs of arc. (25, 26) Vernier

66 alignment (vernier acuity), a classic hyperacuity task where participants discriminate difference in the

67 relative spatial localisation of two or more visual stimuli such as lines or dots has been used in

68 previous studies (27-29). The use of such methods for conditions such as amblyopia (30) and age-

69 related macular degeneration (AMD) (31) have demonstrated perceptual distortions exhibit a similar

70 dissociation from visual acuity as clinical keratoconus indices. Thus, evaluating perceptual distortions

71 may provide a more nuanced characterisation of visual function for ocular diseases.

72

73 In this study, we used a quantitative paradigm based on both vernier alignment and field matching

74 techniques to quantify visual distortion experienced in keratoconus and assess its relation to corneal

75 structural changes. Providing a means to reliably and systematically characterise the visual deficit in

76 keratoconus enables future studies exploring the impact of established treatments upon these deficits.

77

78 **Methods**

79 **Participants:**

80 A total of 25 participants (mean age = 29.84 ± 7.46 years, 15 females) with keratoconus at different

81 disease stages and 25 normal controls (mean age = 22.12 ± 2.62 years, 17 females) were recruited for

82 the study. All participants underwent measurements of the best-corrected monocular visual acuity

83 (BCVA) with Bailey-Lovie log MAR chart after refraction with autorefractor (Topcon KR-8000PA)

84   by an optometrist. The corneal assessment to ascertain keratoconus signs was carried out using

85   Haag-Streit slit-lamp biomicroscope. The corneal mapping was conducted using a corneal

86   topographer (Oculus Keratograph D-35582) and the central corneal thickness (CCT) was measured

87   using anterior segment ocular coherence tomogram (Topcon 3D OCT-2000). A specialist

88   established the keratoconus diagnosis based on the maximum corneal curvature (K_{max}) of ≥ 50.00Ds

89   with topographic keratoconus classification (TKC) grading of >1.0 and the presence of classical

90   keratoconus sign in either eye. The signs considered were Munson's sign, Rizutii's sign, Vogt striae,

91   and Fleischer ring, in addition to scissors reflex on retinoscopy. The clinical details of the keratoconus

92   and control group are presented in Table 1.

93

94   Table 1: Clinical attributes of keratoconus and control participants

Clinical parameters	Keratoconus (n = 50 eyes)	Control (n = 50 eyes)
Best-corrected visual acuity, log MAR, mean (SD), mean Snellen	0.21 (0.27), 6/9.6	-0.09 (0.06), 6/4.8
Refractive error (Sphere), diopter cylinder, mean (SD)	- 2.52 (2.85)	- 1.14 (1.61)
Refractive error (Cylindrical), diopter cylinder, mean (SD)	-3.45 (2.10)	-0.77 (0.90)
Maximum corneal curvature, dioptre, mean (SD)	54.48 (6.09)	45.66 (1.58)
Mean corneal curvature, dioptre, mean (SD)	47.03 (3.96)	44.51 (1.41)
Central corneal thickness, micrometre (µm), mean (SD)	495.34 (47.50)	554.36 (25.71)

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96   **Stimuli and procedure**

97   The experimental stimulus was created and presented using MATLAB (32) software with

98   psychtoolbox extensions (Psychtoolbox 3.0) (33, 34) and presented on a computer screen with the

99   resolution of 1920 x 1080 pixels. The task combined vernier alignment and field matching techniques.

100   The stimuli consisted of eight circles (suprathreshold acuity and contrast) each subtending 0.37° at the

101   viewing distance of 90cm. The task for the observer was to align target circles with computer mouse

102   click in relation to a reference line and circles presented against a 75% contrast grey background

103   monocularly. At the start of the experiment a white central fixation circle (0.14°) and a white

104   horizontal line were presented. This was followed by the presentation of a yellow reference circle

105　(0.37°) at the eccentricity of 0.73° from the central fixation (Figure 1; a). The task for the participant

106　was to align a white target circle with the yellow reference circle at an equal distance from the

107　horizontal reference line (Figure 1; a & b). After the placement of the first circle, the reference line

108　was presented vertically, and the participant aligned the next target circle in the opposite field (Figure

109　1; b & c). Following this, the reference line was removed, and the participant placed another target

110　circle to complete the remaining corner of a "virtual square" (Figure 1, d). Following this, two dots

111　changed colour to orange (reference dots) and the task for the participant was to place the target

112　circles at the mid-point and in alignment with these reference dots (Figure 1, e - g). The process

113　continued until a square shape was completed by placing a total of seven target circles. (Figure 1, h).

114　Participants fixated on a central target (0.14°) throughout the task. There was no time limit for the

115　completion of the task. If the participant reported having made an error with the dot placement (e.g.

116　mis-click), the researcher removed the dot to allow another attempt.
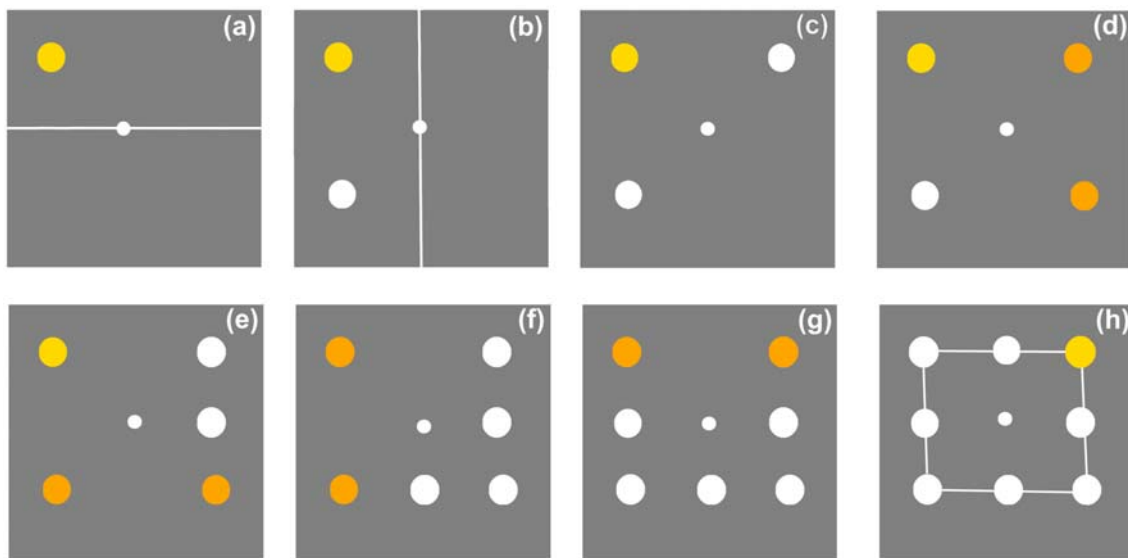
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Figure 1: Schematic representation of the experimental task. The task was to position a supra-threshold contrast white circle in relation to the white line and/or yellow/orange circles to complete a square shape (bottom right panel).

120　a) Starting view for the participant (starting corner is randomised). Participant aligns a white dot (shown in b) with yellow

121　dot on the opposite side of the white line to match the reference space.

122　b) Repeat of a) using vertical reference line and horizontal reference space.

123　c - d) Complete the square by aligning the remaining dots horizontally and vertically.

124　e) Fill in the space between the two orange dots in alignment with the central fixation target.

125   f - g) Repeat step e) on each side to finish reconstructing the square.

126   h) Final image shown to the participant after all clicks are completed.

127   Written informed consent was obtained from all participants once the nature of the experiment was

128   explained. The experiment was completed monocularly with the patient's best correction in place in a

129   dark room, with the computer monitor being the only light source. The distance from the monitor was

130   controlled using head and chin rest. The task was repeated five times and the global distortion index

131   (GDI) and global uncertainty index (GUI) were calculated as the mean and standard deviation

132   respectively of local perceived misalignment of target circles over five trials. (30) The distortion data

133   for both keratoconus and normal controls did not follow a normal distribution (Shapiro-Wilk test, $p <$

134   0.001) hence nonparametric statistics were used for all analyses. The study followed the tenets of

135   Helsinki declaration on human research participants and the research protocol was approved by the

136   Campus Research Ethics Committee of the Faculty of Health, St. Augustine campus, the University of

137   the West Indies.

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139   **Results**

140   The visual distortion measured as the global distortion index (GDI) was higher in keratoconus eyes (n

141      $= 50$, median (M) $= 0.43°$) compared to the control eyes ($n = 50$, $M = 0.29°$), Mann-Whitney $U = 756$,

142      $z = - 3.41$, $p = 0.001$. Similarly, the global uncertainty index (GUI) was also higher in keratoconus

143   eyes ($n = 50$, $M = 0.39°$) compared to the control eyes ($n = 50$, $M = 0.25°$), Mann-Whitney $U = 763$, z

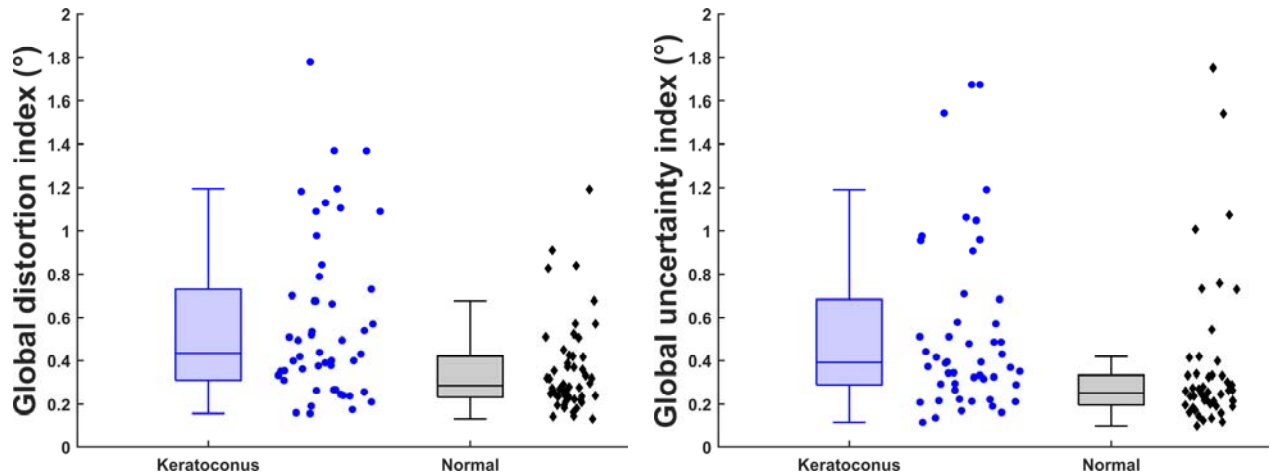144 $= -3.36$, $p = 0.001$. (Figure 2)

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Figure 2: Boxplots comparing global distortion index (left panel) and global uncertainty index (right panel) between keratoconus eyes (*n* = 50) and normal eyes (*n* = 50). Box bounds: upper/lower quartile; horizontal bar within box bounds: median. All data points are also presented.

The relation between clinical parameters and distortion indices (GDI and GUI) were investigated using Spearman's rank order correlation. These are shown for GDI in Figure 3 and GUI in Figure 4 for BCVA (Figure 3a, 4a), maximum corneal curvature (Figure 3b, 4b), central corneal thickness (Figure 3c, 4c) and topographic keratoconus classification (TKC) scores (Figure 3d, 4d). Among the clinical parameters, BCVA strongly correlated with maximum corneal curvature (Spearman's rho (ρ) = 0.73, $p < 0.001$) and moderately correlated with TKC scores ($\rho = 0.49$, $p < 0.001$) but not with central corneal thickness ($\rho = -0.27$, $p = 0.06$). Thus, poorer BCVA was associated with greater maximum corneal curvature and TKC scores.

For the distortion indices, GDI was weakly correlated with BCVA (ρ) = 0.39, $p = 0.005$, Figure 3a), moderately correlated with maximum corneal curvature ($\rho = 0.55$, $p < 0.001$, Figure 3b) and weakly correlated with TKC scores ($\rho = 0.32$, $p = 0.02$, Figure 3d). A moderate negative correlation was also observed between GDI and central corneal thickness ($\rho = -0.43$, $p = 0.002$, Figure 3c). Thus, higher GDI was associated with poorer BCVA, greater maximum corneal curvature and TKC scores, and lower central corneal thickness.
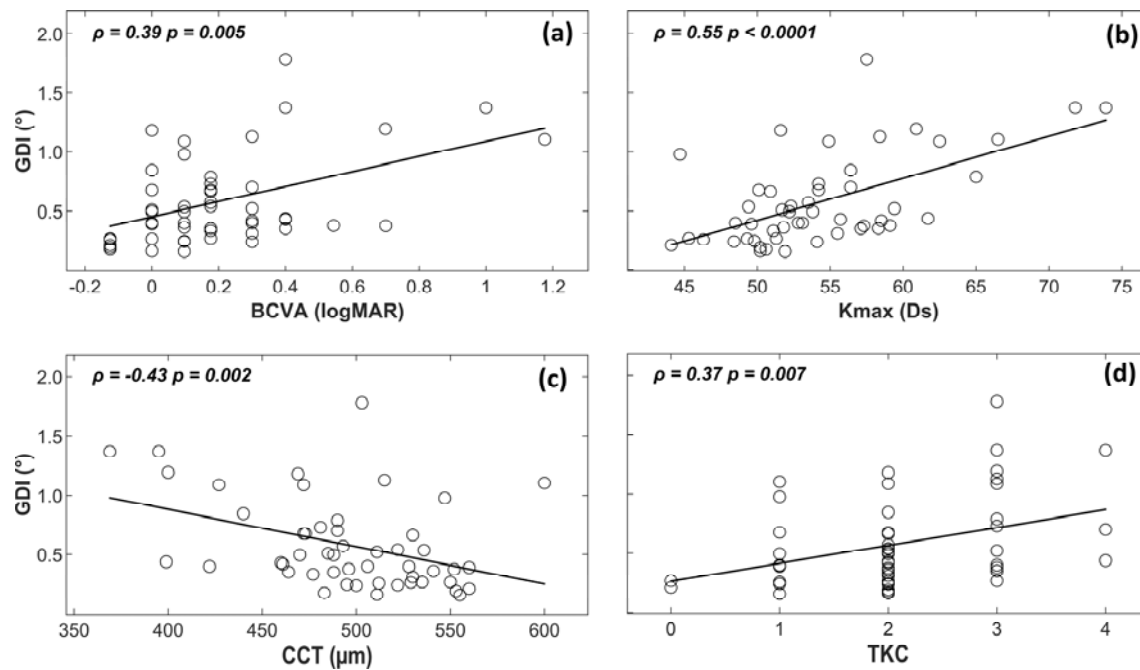
Figure 3: The scatterplots showing correlation between global distortion index (GDI) with a) the best corrected visual acuity (BCVA), b) maximum corneal curvature (K_{max}), c) central corneal thickness (CCT), and d) topographic keratoconus classification (TKC). The red line represents least square regression line. The Spearman's rho (ρ) and the *p* value are also provided.

The global uncertainty index (GUI) also exhibited a weak positive correlation with BCVA ($\rho = 0.35$, $p = 0.01$, Figure 4a), moderate correlation with maximum corneal curvature ($\rho = 0.53$, $p < 0.001$, Figure 4b) and weak correlation with TKC scores ($\rho = 0.32$, $p = 0.02$, Figure 4d). A moderate negative correlation was also observed between the GUI and the central corneal thickness (CCT) ($\rho = -0.44$, $p = 0.001$, Figure 4c). Thus, higher GUI was associated with poorer BCVA, greater maximum corneal curvature and TKC scores, and lower central corneal thickness.
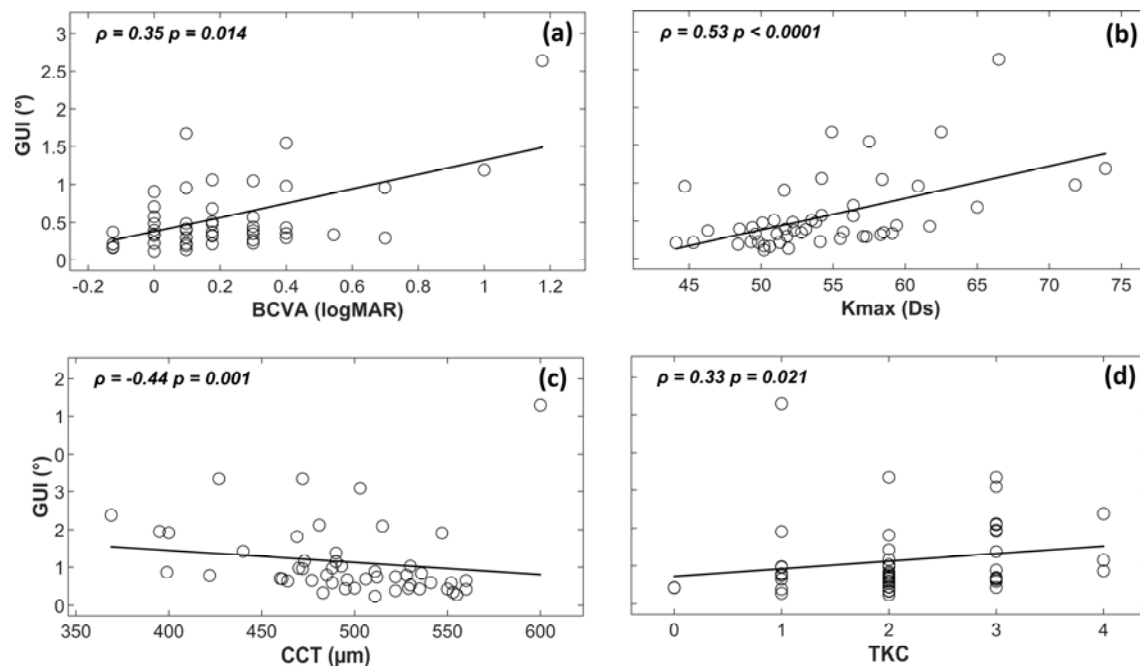
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Figure 4: The scatterplots showing correlation between global uncertainty index (GUI) with a) the best-corrected visual acuity (BCVA), b) maximum corneal curvature (K_{max}), c) central corneal thickness (CCT), and d) topographic keratoconus classification (TKC). The red line represents least square regression line. The Spearman's rho (ρ) and the *p* value are also provided.

Discussion

This study for the first time quantitatively evaluated visual distortion experienced in keratoconus. The results showed that visual distortion was higher in individuals with keratoconus compared to the normally sighted controls. The distortion indices also correlated with commonly measured clinical metrics of keratoconus such as K_{max} and TKC.

The results demonstrate that measurements of visual distortion obtained with our paradigm differentiate individuals with keratoconus from those without. A similar paradigm based on vernier alignment has been used to measure perceptual distortion in amblyopia and AMD before. (30, 31, 35, 36) However these tests are lengthy to conduct in a clinical setting compared to the combined vernier alignment and field matching task used in the current study, which takes just a few minutes to

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199   complete. This renders our paradigm a more viable option for characterising visual distortions

200   associated with keratoconus in clinical settings.

201

202   Both GDI and GUI increased with worsening visual acuity, albeit the correlation was weak. Using

203   similar methods of distortion quantification, distortions were found to be higher in the amblyopic

204   population compared to non-amblyopic controls. (30, 35) Amblyopic observers experience chronic

205   distortion during development and may learn the spatial form of distorted optotypes. In contrast,

206   AMD patients have an acquired deficit later in life and visual distortion (metamorphopsia) arises at

207   the retinal level. Although research concerning the underlying basis of metamorphopsia in these

208   patient groups continues to be limited, it has been suggested that the visual processing stream in such

209   instances may be subject to top-down influences as a result of the slow progressing nature of the

210   aetiologies, potentially resulting in some degree of visual adaptation to the degraded image quality

211   and a resulting dissociation of perceived metamorphopsia from the visual acuity deficit. (31) Such

212   influences may also explain why we found a higher GUI (index of stability of the visual percept) that

213   correlated with certain clinical keratoconus indices.

214

215   In our sample, poorer BCVA was associated with greater maximum corneal curvature ($\rho = 0.73$) and

216   TKC scores ($\rho = 0.49$) but was not significantly correlated with CCT ($\rho = - 0.27$). Previous studies

217   have shown that visual acuity shows a variable degree of correlation with the corneal structural

218   measures and vision related quality of life in keratoconus. (9-11, 37) In comparison, contrast

219   sensitivity has been found to correlate with corneal irregularities (37), higher order aberrations (13),

220   and vision related quality of life (12). However, proper measurement of contrast sensitivity is time

221   consuming and traditional clinical tests of contrast sensitivity such as VisTech chart have limited

222   spatial frequencies for evaluation of moderate to advanced keratoconus. (15) Hence, the distortion

223   test used in the current study could provide an alternative or adjunctive visual measure for

224   keratoconus.

225

226   The visual distortion indices also correlated with commonly measured corneal structural parameters.

227   Both GDI and GUI increased with higher corneal curvature, higher TKC and lower corneal thickness.

228   The maximum corneal curvature (K_{max}) and central corneal thickness better reflect the quality of life

229   measures in keratoconus compared to visual acuity. (38, 39) Distortion measurement could therefore

230   serve as a helpful bridge between clinical indicators and perceived quality of life that is quick and

231   simple to administer.

232

233   In recent times home monitoring of different ocular conditions have been used (31, 40, 41) and these

234   have become even more important due to the COVID-19 pandemic, during which it has been

235   necessary in many instances to constrain in-person clinical interactions to essential care. Various

236   home-based applications implemented on the digital devices show good reliability compared to the

237   hospital-based tests for different ocular conditions. (40-44) As far as we are aware, there are no

238   systematic measures of distortion in keratoconus that could be utilised in this context. Proper

239   monitoring in keratoconus could ensure timely medical intervention such as collagen crosslinking but

240   requires assessment by an eye care professional using specialist imaging equipment. A simple

241   monocular visual task such as that used in the current study could be easily transformed into a home-

242   based tool. This also holds promise for individuals living with keratoconus in remote or rural areas

243   with limited specialist access. In future, we will develop a version of the distortion test for use on

244   personal or portable computing devices, to explore the use of the test as a home based tool for

245   keratoconus.

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247   Some limitations can be identified for our study. Firstly, our paradigm provides information about

248   distortion magnitude, but less about the individual's subjective percept, e.g. magnification, barrel

249   distortion, etc. If clinically relevant, practitioners can store the square drawings to retain as a way of

250   visually monitoring distortion over time. However, at present we are not able to offer a systematic

251   method for detecting significant changes in the shape of the constructed square, which has the

252   capacity to change significantly while yielding similar GDI and GUI measurements. This could be

253   developed in future using image processing techniques or through methods such as subdivision into

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254   quadrant-based GDI and GUI measurements. Additionally, the value of a measurement tool to detect

255   progression of keratoconus remediation following treatment will depend on the repeatability of

256   distortion measurements, which is the focus of future work. Secondly, this was a cross-sectional

257   study and we are unable to provide information about the extent to which treatments for keratoconus

258   such as cross-linking may affect such measurements. As the correlation between BCVA and our

259   distortion measures was modest, we cannot be certain whether interventions to improve visual acuity

260   will impact GDI and GUI. As such, whether these distortion measures could be used to support

261   clinical decision-making about keratoconus interventions or as a treatment outcome measure should
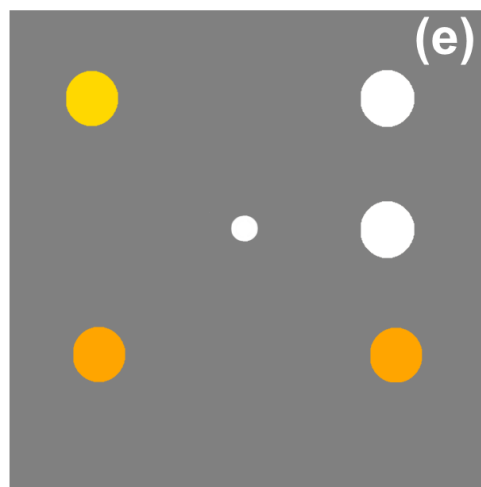
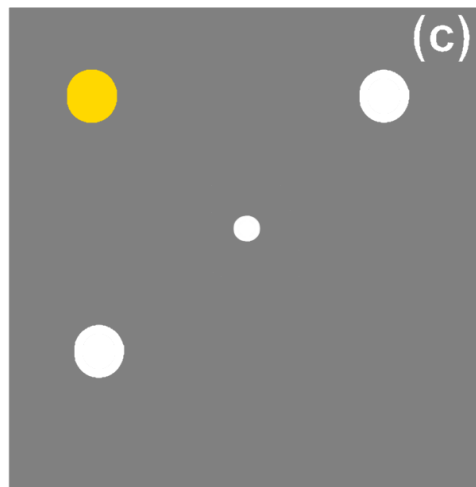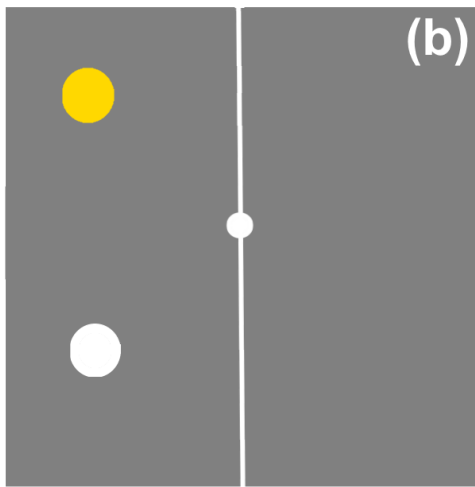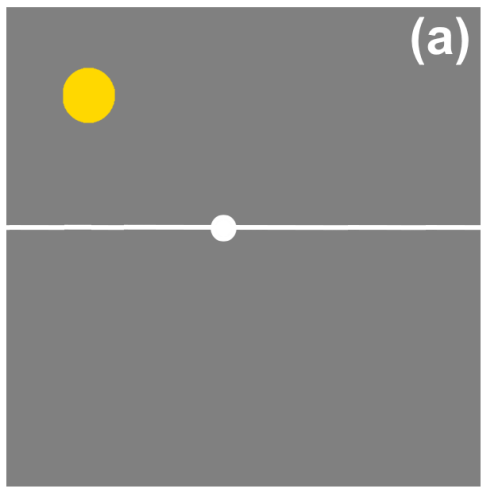262   be a focus of future work.
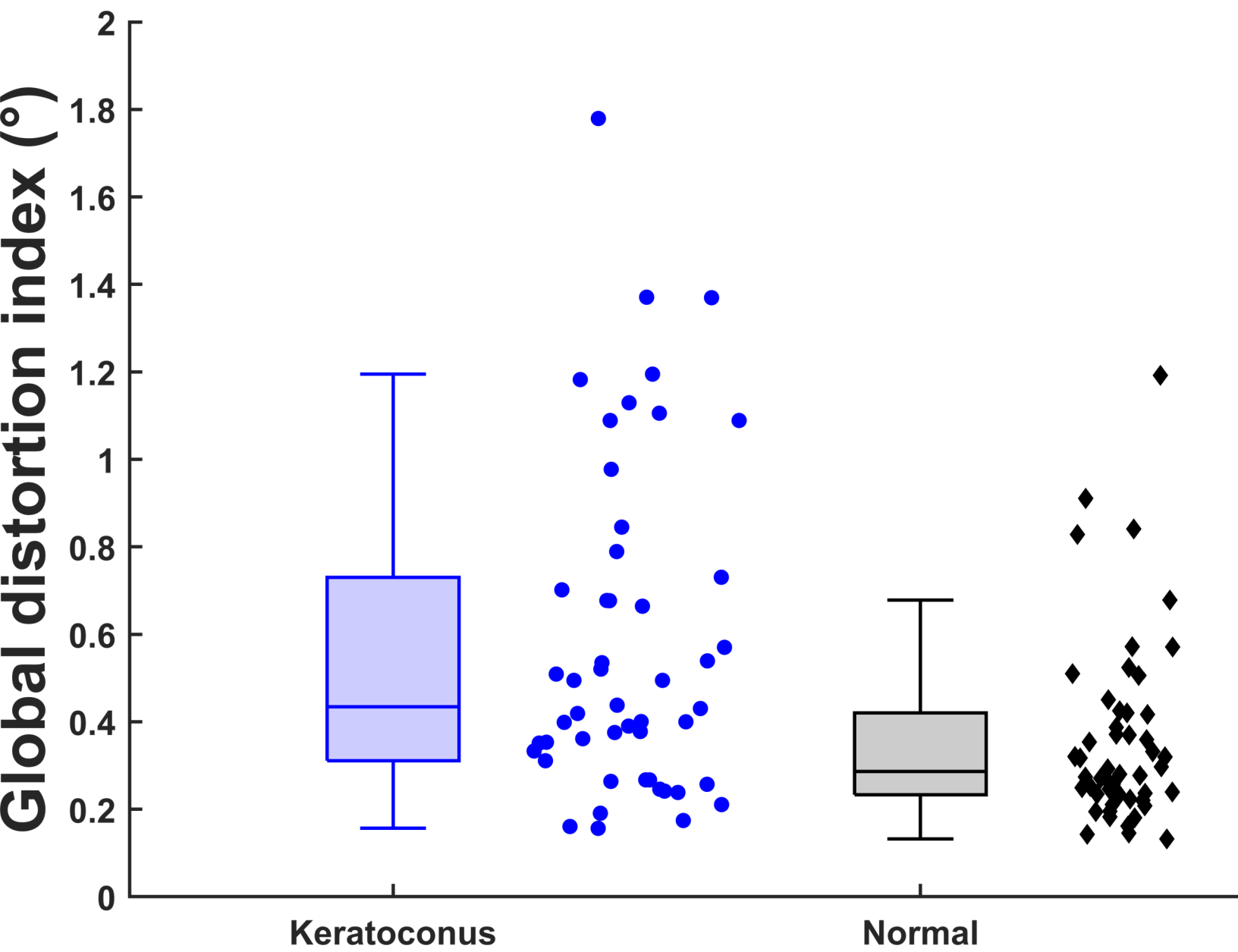
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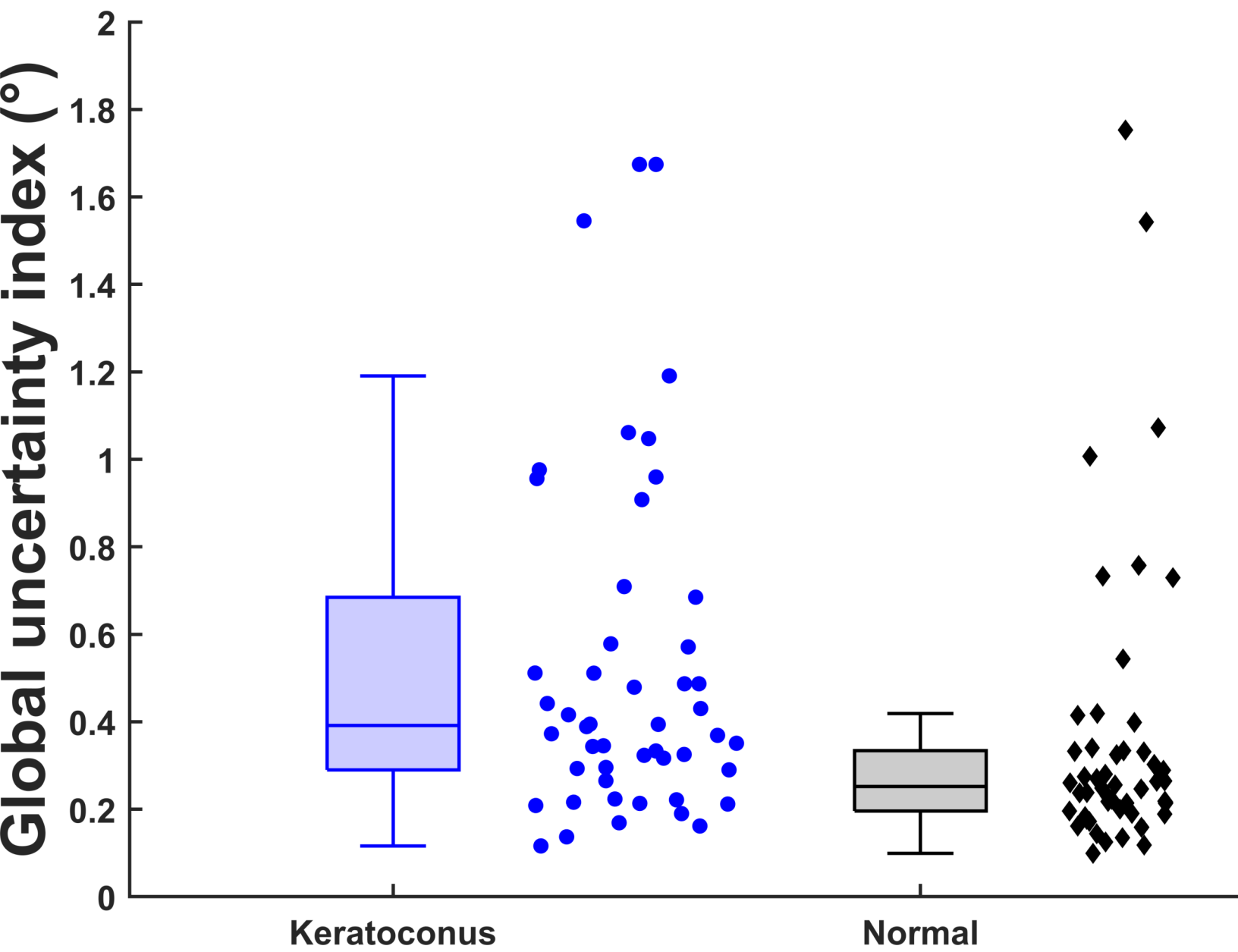292   Keratoconus subjects. Scientific Reports. 2021;11(1):12971.

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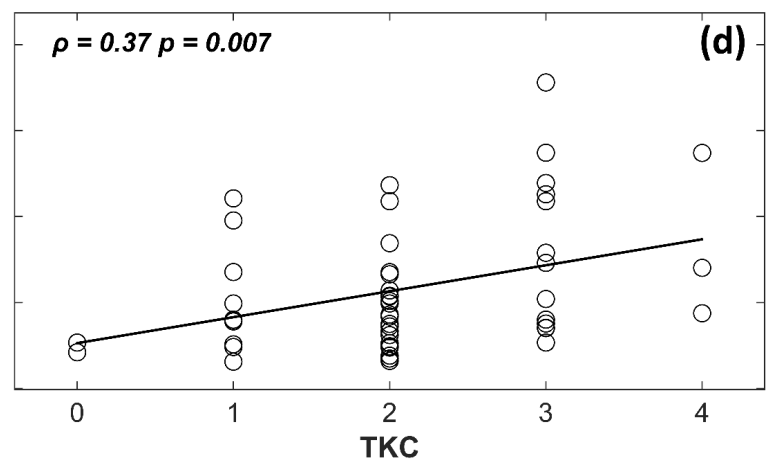342   During/Following Routine Amblyopia Treatment. Invest Ophthalmol Vis Sci. 2016;57(10):4045-54.
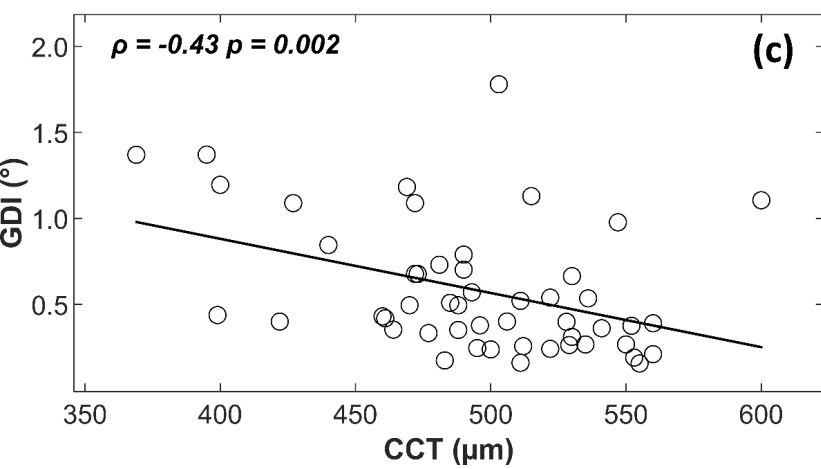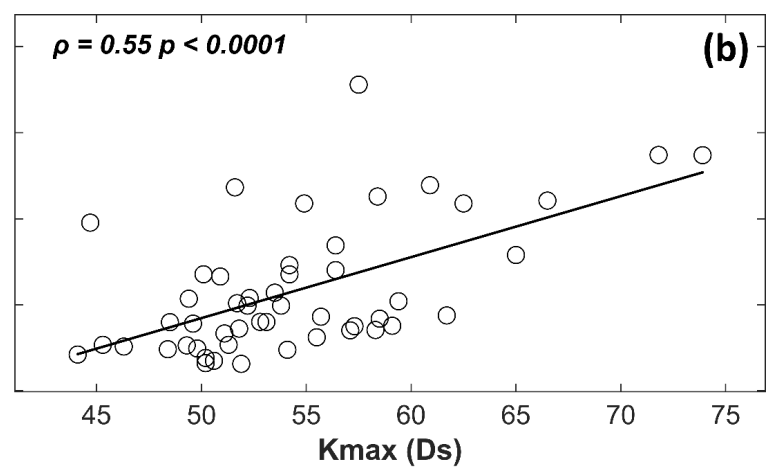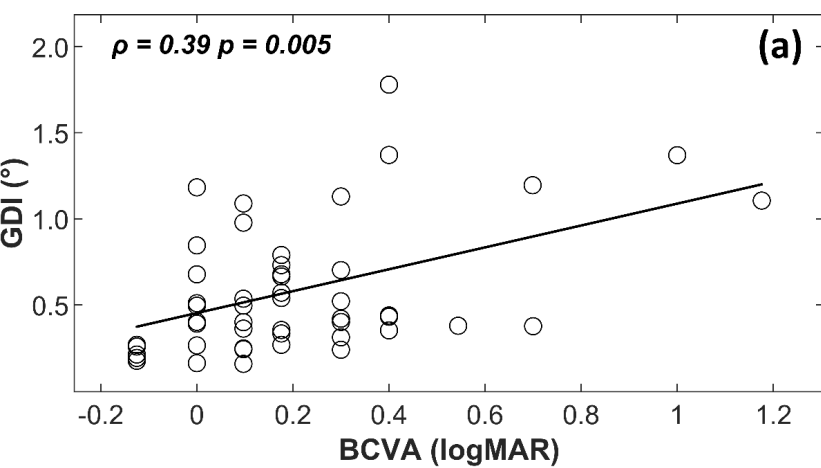
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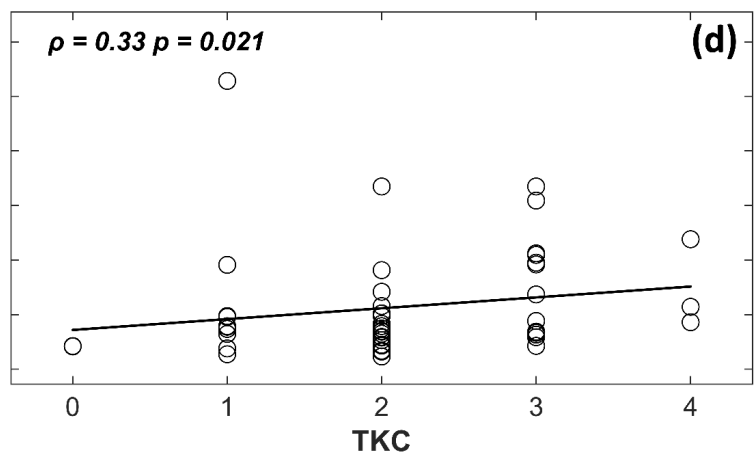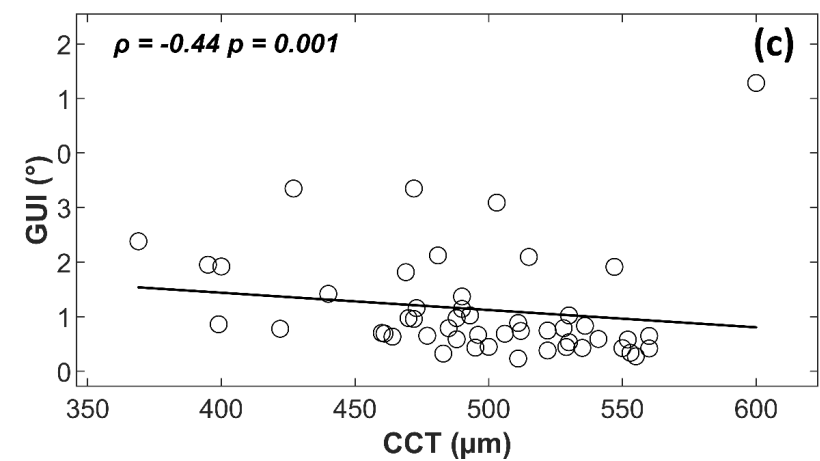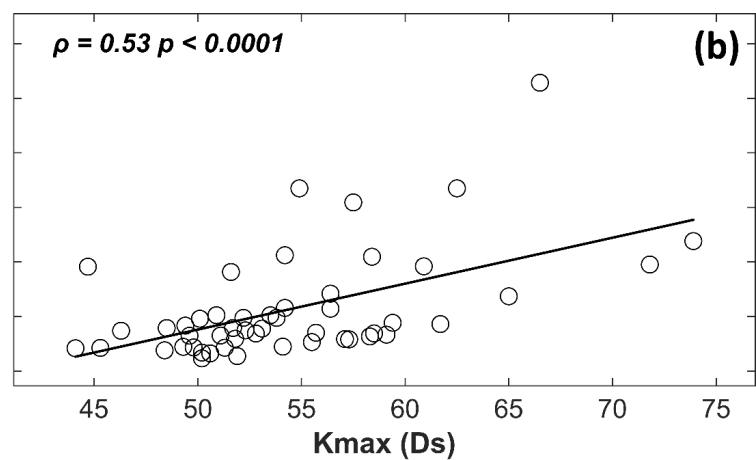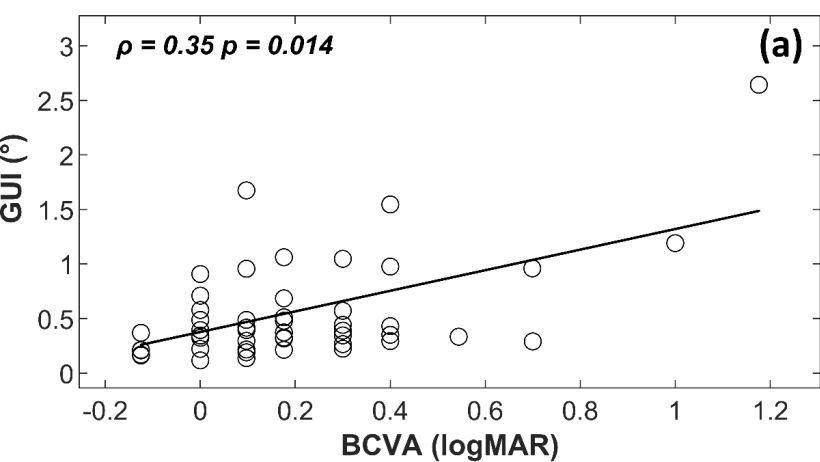
366

(a) $\rho = 0.39$ $p = 0.005$

(b) $\rho = 0.55$ $p < 0.0001$

(c) $\rho = -0.43$ $p = 0.002$

(d) $\rho = 0.37$ $p = 0.007$

(a) $\rho = 0.35\ p = 0.014$

(b) $\rho = 0.53\ p < 0.0001$

(c) $\rho = -0.44\ p = 0.001$

(d) $\rho = 0.33\ p = 0.021$
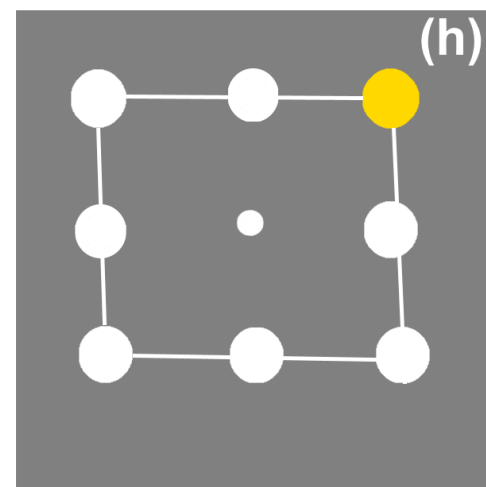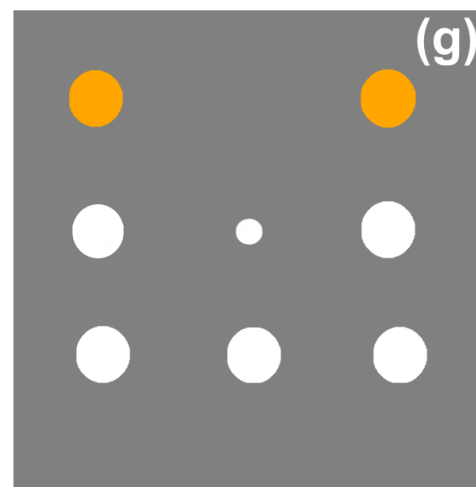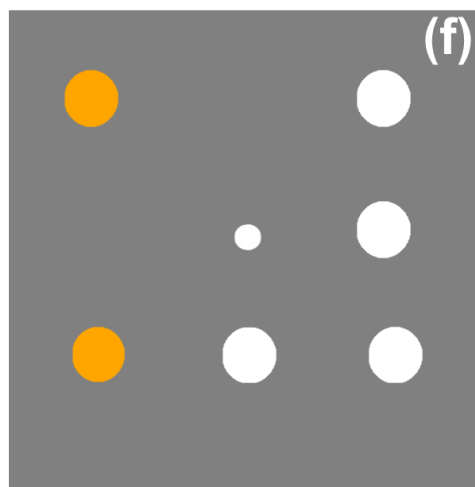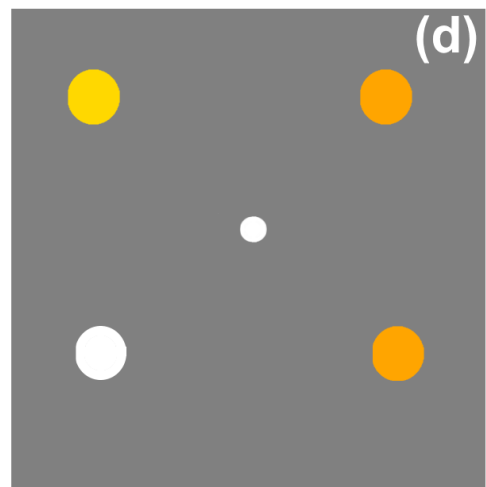
Clinical parameters	Keratoconus (n = 50 eyes)
Best-corrected visual acuity, log MAR, mean (SD)	0.21 (0.27)
Refractive error (Sphere), diopter cylinder, mean (SD)	- 2.52 (2.85)
Refractive error (Cylindrical), diopter cylinder, mean (SD)	-3.45 (2.10)
Maximum corneal curvature, dioptre, mean (SD)	54.48 (6.09)
Mean corneal curvature, dioptre, mean (SD)	47.03 (3.96)
Central corneal thickness, micrometre (μm), mean (SD)	495.34 (47.50)

Control (n = 50 eyes)
-0.09 (0.06)
- 1.14 (1.61)
-0.77 (0.90)
45.66 (1.58)
44.51 (1.41)
554.36 (25.71)