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ORIGINAL ARTICLE

Can children measure their own vision? A comparison of three new contrast sensitivity tests

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Abstract

Purpose: To investigate the feasibility of children measuring their own contrast sensitivity using a range of tablet- and paper-based tests.

Methods: Forty children aged 5–15 years with amblyopia ($N = 10$), bilateral vision impairment ($N = 10$) or good vision ($N = 20$) measured their own vision on a screen-based optotype test (Manifold), a gamified vision test (PopCSF) and a paper-based test (Spotchecks) in a laboratory with minimal supervision. Completion rate, test–retest repeatability, test duration and participants' preferences were recorded for each test.

Results: Most participants (36/40) were able to perform all three tests. All tests were correlated with clinically measured visual acuity and contrast sensitivity ($p < 0.001$). The 95% coefficient of repeatability was 0.30 dB for Manifold, 0.29 dB for PopCSF and 0.13 dB for Spotchecks. All tests differentiated between children with reduced contrast sensitivity and control participants. PopCSF and Spotchecks were also able to differentiate between children with amblyopia and those with good vision. Median test time was 152, 130 and 202 s for Manifold, PopCSF and Spotchecks, respectively. Twenty-two participants preferred the PopCSF test, 10 preferred Spotchecks and 6 preferred Manifold. Thirty-nine out of the 40 children (98%) said they would measure their own vision at home using at least one of these tests every month.

Conclusions: Children and young people can test their own contrast sensitivity with repeatable results. Of these three tests, the most repeatable was Spotchecks, the quickest was PopCSF and participants' favourite was PopCSF. Nearly all of the participants said they would be willing to use at least one of the three tests at home.

KEYWORDS
amblyopia, contrast sensitivity, home monitoring, low vision

INTRODUCTION

Contrast sensitivity is a fundamental aspect of vision, which determines the threshold between the seen and the unseen.[1] Contrast sensitivity is associated with vision-related quality of life in people with eye disease,[2–4] and having better contrast sensitivity is associated with better performance on everyday tasks as diverse as reading, writing, recognising faces, telling the time on a clock, walking, balancing, pouring liquids and using kitchen utensils.[5–11] The contrast sensitivity function (CSF) is altered in people with many eye diseases,[12–19] including those who have been treated for amblyopia and subsequently achieved good visual acuity.[20]

Despite its clear relevance to visual function, contrast sensitivity is not widely measured in clinical practice.[21] Where it is measured clinically, an optotype test such as the Pelli–Robson[22] or MARS chart,[23] a 'vanishing' test such as Hiding Heidi[24] or a detection test like Spotchecks (previously known as CamBlobs) is most often used.[25] All of these techniques measure only one point on the CSF, approximately corresponding to the peak of the curve, rather than describing the whole function.

More recently, tests have been developed that measure more points on the CSF, using Bayesian adaptive algorithms like QUEST,[1,26,27] to calculate the area under the entire CSF. These provide a more holistic indication of visual function. Manifold[28] and PopCSF[29] are two such tests, which measure contrast sensitivity using an optotype test and a 'bubble popping' game, respectively. The Manifold test has been used in adults with myopia,[30] multiple sclerosis[31] and retinal vein occlusion,[32] as well as in adolescents with amblyopia.[33] The more gamified PopCSF test has been used in children with amblyopia and has been shown to correctly identify moderately amblyopic eyes from fellow eyes.[29]

One of the aims of the current work was to start to understand whether these tests could be used in a paediatric home setting. There is increasing interest in home vision testing, particularly since the advent of the COVID-19 pandemic.[34,35] Remote consultations are seen as more convenient,[36,37] and have a lower environmental impact[38] than conventional hospital eye clinic appointments. Remote assessment can be particularly helpful for children and young people, as it can reduce time away from school, as well as reducing parental time away from work or caring responsibilities. This is especially relevant for children undergoing amblyopia treatment who may have their vision checked every 8–12 weeks,[39] and for those with other conditions who may only attend ophthalmology appointments annually, for whom there is a risk that vision changes between appointments will not be detected. Several clinical groups have measured visual acuity at home in children using printed tests,[40] phone apps[41] or web-based systems,[42] and a systematic review protocol to investigate the effectiveness of these techniques has been published.[43] Despite its relevance in the detection and monitoring of amblyopia,[44,45] home testing of contrast sensitivity in children has not been assessed.

Here we investigated three novel contrast sensitivity tests that may be suitable for use as a home-based test: (1) Manifold, a screen-based optotype test running on an Android tablet; (2) PopCSF, a 'gamified' test that runs on an iPad and (3) Spotchecks, a pen-and-paper-based test. We demonstrated these tests to children with a variety of eye disease and asked them to perform them with minimal supervision. Finally, we asked whether they would be willing to perform these tests at home.

Key points

- The Manifold, PopCSF and Spotchecks tests can all be used to measure contrast sensitivity in children between 5 and 15 years of age, including those with moderate vision impairment.
- Repeatability was good for all three tests, with limits of agreement indicating that a difference in contrast sensitivity of 0.3 log units can be detected with 95% accuracy by all three of the tests.
- Despite taking an average of between 2 and 4 min per test, most children said they would be willing to perform these tests at home.

METHODS

Participants and recruitment

Participants were 5–15 years of age. Control participants were recruited through friends and family of the study team and colleagues. All had a distance visual acuity of 0.20 logMAR (6/9.5) or better in each eye (with glasses, if required) and no history of eye disease (other than refractive error of less than ±5.00 DS spherical equivalent).

Participants with amblyopia were recruited from clinics at Moorfields Eye Hospital, London. All had been diagnosed with amblyopia and had an interocular visual acuity difference of at least 0.2 logMAR (with best refractive correction) and/or were currently receiving occlusion therapy for amblyopia. All had a visual acuity of 0.20 logMAR or better in their better eye with their best refractive correction.

Participants with vision impairment were recruited from the low vision clinic at Moorfields Eye Hospital. All children met the ICD-11 definition of vision impairment and had corrected visual acuity poorer than logMAR 0.30 (6/12) with both eyes open, a binocular visual field of less than 10° and/or functional deficits in higher cerebral centres.

Letter contrast sensitivity

Letter contrast sensitivity was measured using a Pelli–Robson chart (Precision Vision, precision-vision.com) in those with good vision or a MARS chart (Mars Perceptrix, marsperceptrix.com) for those with amblyopia or vision impairment. These charts have been shown to provide equivalent results.[46]

Manifold (Screen-based optotype vision test)

Shown in Figure 1a, the Manifold[27] (Adaptive Sensory Technology Ltd, adaptivesensorytech.com) is a tablet-based

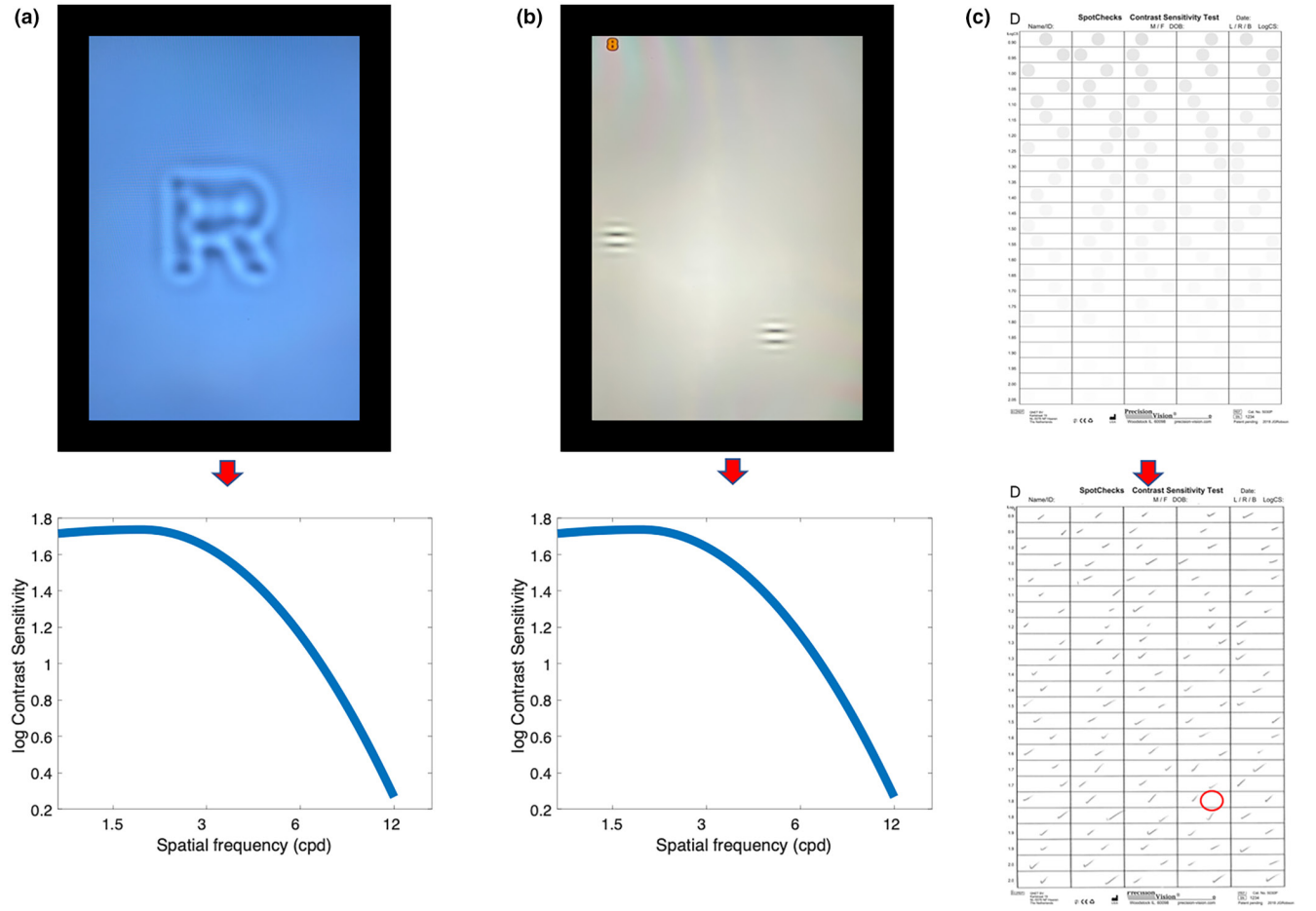

FIGURE 1 The three contrast sensitivity (CS) tests (top panels) and their corresponding outputs (lower panels). (a) Manifold test and its constructed result. (b) PopCSF and its constructed result (grey region represents the area under the CSF). (c) Spotchecks test and its completed form. Second error (final score) marked with a red circle to indicate threshold logCS.

letter-optotype test that uses the quickCSF algorithm to estimate the CSF.[47] Thirty filtered Sloan letters were presented sequentially, with varying Michelson contrast and spatial frequency. Participants were asked to identify each letter by touching the corresponding letter on a response screen which appeared after each stimulus presentation. A'?' response was allowed if participants could not identify the letter. A CSF was calculated and the area under this curve reported.

The Manifold test was performed on a calibrated Samsung Tablet (Galaxy Table A 8.4″ 2020; Samsung Electronics Co. Ltd, samsung.com) running the Manifold Home Monitor app. Overhead room lights were turned off during testing, with the room being lit by a table lamp and an illuminated test chart (room illuminance 54 lux). The screen was set to maximum brightness (background luminance 102 cd/m^2; Minolta CS-100, sensing.konicaminolta.us).

Participants viewed the screen from 50 cm (with the distance monitored by the device, which instructed participants to move closer to or further away from the screen, as required, until the viewing distance was determined to be within acceptable bounds). They were asked to identify each test letter and to touch the correct response on the response screen. They were advised that some of the letters would be too small or too faint to see. If they could not identify the letter, they were asked to either guess or tap the '?' response. Test time was recorded as the interval between the onset of the first and the response to the last test stimulus, identified from the device's log file. Area under the log CSF was extracted from the same log file.

PopCSF (Gamified vision test)

Shown in Figure 1b, PopCSF[29] is a tablet-based, gamified test that uses QUEST+[26] to estimate the CSF. Participants were asked to 'pop' moving Gabor patches by touching them as they moved randomly around the screen. The spatial frequency and Michelson contrast of each stimulus varied adaptively. The test was designed to be engaging and fun for children to use, but as a consequence, there is less control over where on the retina the stimuli appear (as the targets appear and move across any point on the screen). As shown in Figure 2, the test constructs a CSF based on G_{max}

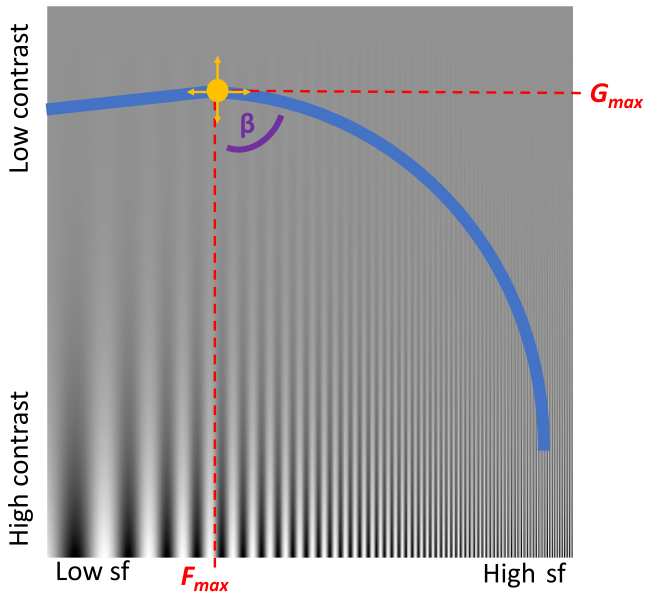

FIGURE 2 Parameters of the CSF measured by PopCSF. The blue line shows an example CSF. The yellow circle shows the point of peak contrast sensitivity (G_{max}) and its spatial frequency (F_{max}). β indicates the angle of decline of the CSF after G_{max}. sf, spatial frequency.

(peak contrast sensitivity), F_{max} (the spatial frequency associated with the peak contrast sensitivity) and β (the slope of the high-spatial-frequency drop of the CSF), using an adaptive maximum likelihood algorithm, mathematically similar to the quickCSF algorithm used by the Manifold.

The PopCSF test was run on an Apple iPad Pro (11-inch, 2nd generation, apple.com) running iOS 15.3. As with the Manifold, the overhead room lights were turned off, but the room was lit by a table lamp and an illuminated test chart (room illuminance 54 lux). The screen was set to maximum brightness (background luminance 274 cd/m^2; Minolta CS-100, sensing.konicaminolta.us). Example stimuli were shown on a setup screen and participants were warned that some targets would be too faint for them to see.

Participants viewed the screen from 50 cm (with the distance monitored by the device, which corrected stimulus size in near-real time using viewing distance data from the Apple TrueDepth camera). During the assessment, participants were asked to touch all targets that they identified on the screen. Test time was recorded as the interval between the onset of the first and the last test stimulus, identified from the device's log file. F_{max}, G_{max} and β values were extracted from the log files and the area under the CSF was calculated using a bespoke MATLAB program (Mathworks, uk.mathworks.com/products/matlab.html).

Spotchecks (Paper-based vision test)

Shown in Figure 1c, Spotchecks[25] (Precision Vision, precision-vision.com) is a pen-and-paper, single-use contrast sensitivity test. Each test consists of a single sheet of A4 paper containing a grid of 120 boxes, each containing a grey spot in one of five locations. The spots range from 0.90 to 2.09 log units of Weber contrast (12.5%–0.8%). Participants were asked to mark the target in each box and encouraged to complete the entire sheet, guessing where necessary. The test gives a summary measure of contrast sensitivity similar to that provided by the Pelli–Robson contrast sensitivity chart[25,48] (manufactured by the same suppliers). In principle, the measure is closely related to the peak of the CSF (G_{max}), though exactly which part of the CSF the test examines depends on viewing distance (which was not restricted, and so was liable to change slightly throughout testing).

During testing, overhead room lights were switched on (illuminance 540 lux). Participants viewed the chart from approximately 40 cm, although they were allowed to self-select their viewing distance, replicating previous work using this test.[48] They were asked to mark the target in each box and encouraged to complete the entire sheet, guessing if necessary. The time taken from the first tick to the last tick was recorded using a stopwatch.

Procedure

Children wore their habitual refractive correction throughout testing. Those with good vision or amblyopia performed all three tests monocularly, with the fellow eye patched. For children with good vision, the test eye was the one with better visual acuity. If visual acuity was equal, the dominant eye was tested, as determined using a pointing test.[49] If visual acuity was equal and eye dominance could not be determined, then the right eye was used. For children with amblyopia, the test eye was the amblyopic eye, although the nonamblyopic eye was also tested. Children with bilateral vision impairment performed all tests with both eyes open.

The three tests were performed in random order, using a Latin square. Each test was performed twice, sequentially, with a short gap in between each test. For children with amblyopia, the test was performed twice on the amblyopic eye and once on the fellow eye, with the first eye determined at random for each test. In other words, children with good vision and vision impairment performed six tests (3 instruments × 2 tests) and those with amblyopia performed nine tests (3 instruments × 2 tests on the amblyopic eye, plus 3 instruments × 1 test for the fellow eye).

After each test was completed, participants were asked whether they would be willing to perform that test at home and if so, how often (daily, weekly or monthly). They were also asked whether they would describe the test as 'fun', 'OK' or 'boring', and for any additional comments about the test. Finally, participants were asked to rank the three tests in order, from the most to the least favourite.

Level of supervision

The researcher and a parent or carer remained in the room throughout testing. After explaining how each test was performed, the accompanying adults did not intervene with testing other than providing general encouragement (e.g., 'well done, you're doing really well'). This level of supervision was designed to be equivalent to how we anticipate parents would act during home testing: encouraging but not interfering with data collection.

Statistical analysis

Test accuracy was determined by Pearson's correlation with the reference standard (letter contrast sensitivity), as was the agreement between the three novel tests. Between group differences for each test were identified using the Tukey–Kramer honestly significant difference test. Repeatability was evaluated using Bland–Altman techniques[50] and internal validity using Cronbach's alpha.[51] Simple descriptive statistical techniques were used for all other analyses. MATLAB was used for all statistical tests.

Ethics statement

The research adhered to the Declaration of Helsinki. Ethical approval for participants with good vision was given from the UCL Research Ethics Committee (approval number 0623/005). Ethical approval for participants with eye disease was given from the London–Surrey Borders Research Ethics Committee and approved by the Health Research Authority (approval number 305561). All participants were provided with age-appropriate details about the study and assented to participating. Written informed consent was provided by the parent or carer.

RESULTS

Participants

Twenty control participants, 10 children with amblyopia and 10 children with vision impairment were recruited. Participants were 5–15 years of age (mean: 9.3 years; SD: 2.7; see Figure 6 for exact distribution). Children with amblyopia were significantly younger (mean: 6.6 years) than the controls (mean age 10.2 years; two sample *t*-test, $t_{28} = 4.46$, $p < 0.001$) and those with vision impairment (mean age: 10.2 years; two sample *t*-test, $t_{18} = 3.87$, $p < 0.005$). Twenty-four of the participants (60%) were female.

Control participants had mean visual acuity of 0.01 logMAR (SD: 0.05) and mean Pelli–Robson contrast sensitivity of 1.65 log units (SD: 0.07 log units). In children with amblyopia, mean visual acuity was 0.44 logMAR in the amblyopic eye (SD: 0.30) and 0.06 logMAR (SD: 0.06) in the fellow eye, with a mean intraocular difference of 0.38 logMAR (SD: 0.29). Mean contrast sensitivity was 1.49 log units (SD: 0.40) in the amblyopic eye and 1.61 log units (SD: 0.21 log units) in the fellow eye.

Children with vision impairment had a mean visual acuity of 0.50 logMAR (SD: 0.27) with both eyes open and mean contrast sensitivity with the MARS chart was 1.53 log units (SD: 0.25). Two children had inherited retinal disease (one with achromatopsia and one with retinitis pigmentosa). Two had vision impairment secondary to high myopia. The remaining six children had nystagmus, albinism, anterior segment dysgenesis, hemianopia, optic nerve hypoplasia and glaucoma, respectively.

Test feasibility (completion rates)

The Manifold test was completed twice by 36 of the 40 participants (90%). No stimuli could be identified for one child with severe amblyopia (VA 1.14 logMAR) and one child with vision impairment reported that the stimulus display was 'too quick' and could not identify any of the letters. For two control participants, the test could not be completed as the device was not sufficiently charged, due to investigator error. For a further two participants (one control subject and one with amblyopia), the test was completed twice, but data were not recorded for one of the two test sessions due to an unknown technical error.

The PopCSF test was completed twice by all 40 participants (100%). In two control participants, data were not recorded for the second test due to the device failing to accurately record head position, an error that was corrected subsequently in a software update.

The Spotchecks test was completed twice by all 40 participants (100%), and three times by 9 of the 10 participants with amblyopia. One participant with amblyopia did not have their nonamblyopic eye assessed due to time constraints.

For participants with amblyopia, Manifold and PopCSF were completed for the fellow eye in all cases. Spotchecks was not performed on the fellow eye for one participant due to time constraints.

Test accuracy (agreement with reference standard)

Table 1 and Figure 3 show median primary outcome values for each of the tests performed. All three of the experimental tests were correlated with letter contrast sensitivity (Pearson's correlation coefficient: Manifold: $r_{35} = 0.61$, $p < 0.001$; PopCSF: $r_{39} = 0.64$, $p < 0.001$; Spotchecks: $r_{39} = 0.69$, $p < 0.001$). Results from all three tests were linearly correlated with each other (Pearson's correlation, $p < 0.001$ for all comparisons, Figure 4).

Table 2 shows a comparison between the amblyopic and nonamblyopic eye of the participants with amblyopia. These data indicate that visual acuity remains the most reliable way of differentiating the amblyopic eye from the

TABLE 1 Median (IQR) result for each test for each group of participants.

	Median (IQR)			
	Pelli–Robson letter contrast sensitivity (logCS)	**Manifold AUCSF (logCS)**	**PopCSF AUCSF (logCS)**	**Spotchecks CS (logCS)**
Control	1.65 (0.15)	1.31 (0.22)	1.52 (0.17)	1.88 (0.09)
Amblyopia	1.60 (0.18)	1.17 (0.45)	1.04 (0.63)**	1.63 (0.33)**
Vision impairment	1.62 (0.33)	0.90 (1.01)*	0.89 (1.05)**	1.75 (0.26)

Note: Asterisks indicate values which are significantly different from control subjects (*Tukey-Kramer honestly significant difference (HSD) test $p < 0.05$; **Tukey-Kramer HSD test $p < 0.01$).

Abbreviations: AUCSF, area under the contrast sensitivity function; CS, contrast sensitivity; HSD, honestly significant difference.

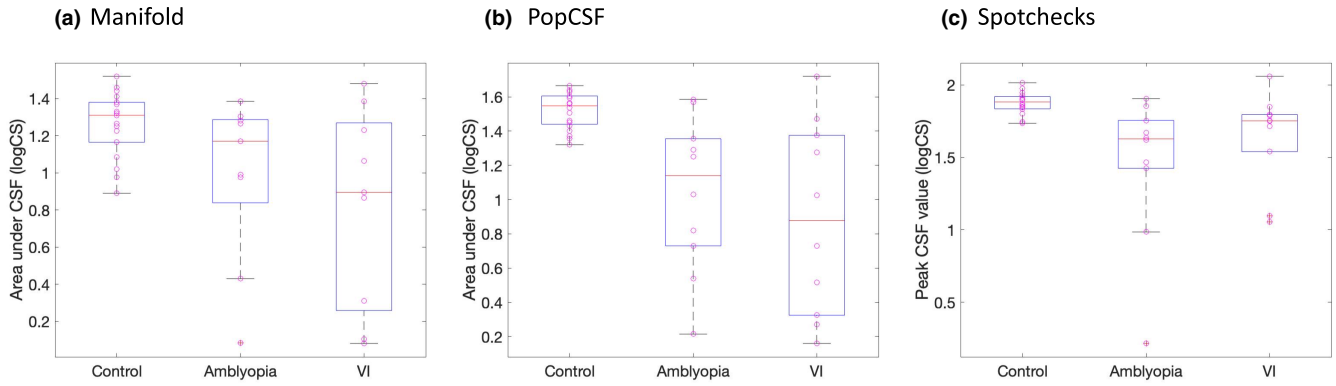

FIGURE 3 Box plots for (a) Manifold, (b) PopCSF and (c) Spotchecks, for each group of participants. Circles show the mean result for each participant (average of two tests). Red lines show group medians. Blue boxes show the 25th–75th percentile. VI, vision impairment.

fellow eye (unsurprisingly, as our definition of amblyopia was an interocular difference in visual acuity). All of the novel tests performed at least as well as letter contrast sensitivity in identifying the eye with amblyopia.

Test reliability (test–retest repeatability)

Figure 5 shows Bland–Altman plots for participants who completed two tests for Manifold ($n = 34$), PopCSF ($n = 37$) and Spotchecks ($n = 40$). The 95% coefficient of repeatability for the Manifold, PopCSF and Spotchecks tests were 0.30, 0.29 and 0.13, respectively. The respective values of Cronbach's alpha were 0.97, 0.97 and 0.99, indicating internal consistency for all three tests.[52]

Effects of age

There was a trend towards older participants having higher logCS values on all three tests, but this did not reach statistical significance (linear correlation shown by the blue line in Figure 6; Manifold $r^2 = 0.007$, $p = 0.62$; PopCSF $r^2 = 0.003$, $p = 0.73$; Spotchecks $r^2 = 0.007$, $p = 0.62$). For control participants, there was a small but nonsignificant trend towards older children having better contrast sensitivity (shown with the green line on the figure; Manifold $r^2 = 0.19$, $p = 0.07$; PopCSF $r^2 = 0.10$, $p = 0.02$; Spotchecks $r^2 = 0.11$, $p = 0.16$).

As shown in Figure 7, there was no effect of age on the repeatability of any of the three tests (Manifold $r^2 = 0.02$; PopCSF $r^2 = 0.11$; Spotchecks $r^2 < 0.01$; all $p > 0.05$).

Test duration

Median (IQR) test duration for Manifold, PopCSF and Spotchecks was 152 (40), 130 (32) and 202 (80) s, respectively. Table 3 and Figure 8 show the duration for each group of participants on each test. There was a significant difference in test duration between the three tests (Kruskal–Wallis test, $\chi^2 = 51.8$, $p < 0.001$).

Test duration was significantly longer for participants with amblyopia than for control participants on Manifold (Wilcoxon test, $Z = -3.24$, $p = 0.001$) and significantly shorter for those with amblyopia than for control participants on PopCSF (Wilcoxon $Z = 1.98$, $p = 0.048$). There were no other significant differences between participant type and test time (all $p > 0.05$).

Children's preferences and views regarding the frequency of home testing

The most preferred test was the PopCSF test (22/38 participants), followed by the Spotchecks test (10 participants) and the Manifold test (6/38). The remaining two participants

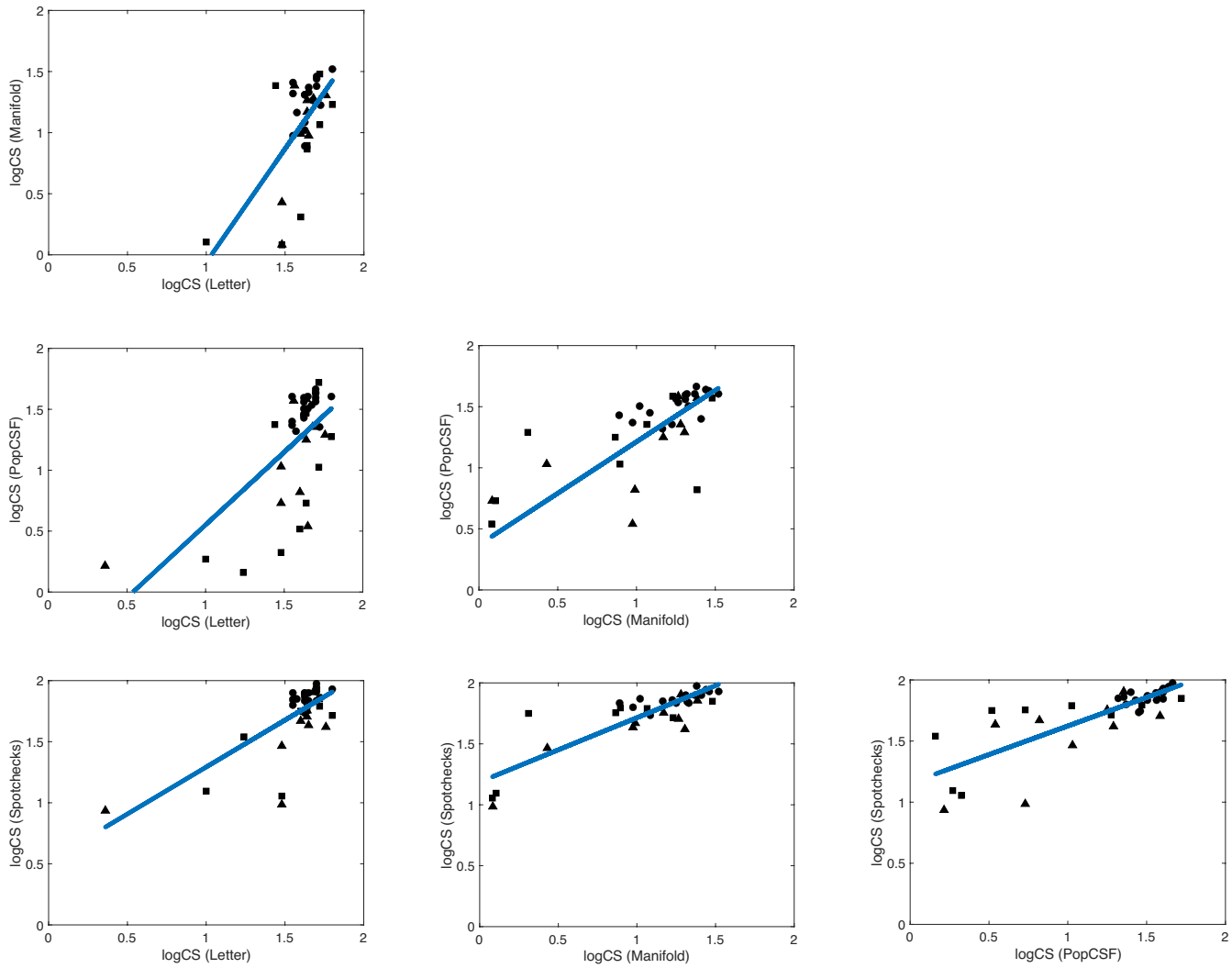

FIGURE 4 Scatterplots showing the relationship between all four tests. 'Letter' shows clinical contrast sensitivity (CS) measurement (Pelli–Robson or MARS test). Circles, control participants; triangles, amblyopes; squares, those with vision impairment. The linear regression is also indicated.

TABLE 2 Median (IQR) result for each test for the amblyopic and nonamblyopic eye of the amblyopic participants.

	Median (IQR)				
	Visual acuity (logMAR)	**Letter contrast sensitivity**	**Manifold AUCSF (logCS)**	**PopCSF AUCSF (logCS)**	**Spotchecks CS (logCS)**
Amblyopic eye	0.37 (0.30)	1.62 (0.15)	1.17 (0.31)	1.14 (0.59)	1.65 (0.24)
Fellow eye	0.09 (0.06)	1.65 (0.17)	1.21 (0.37)	1.38 (0.70)	1.79 (0.52)
Sensitivity of identifying amblyopic eye (true positive rate)	1.0	0.60	0.67	0.60	0.78

Abbreviations: AUCSF, area under the contrast sensitivity function; CS, contrast sensitivity.

did not complete all three tests due to equipment failure. There were no obvious group differences, with the gamified PopCSF test being the most popular across all three groups, but with no clear consensus in any group (control participants, 9/18; amblyopia 8/10; vision impairment 5/10).

One participant (2.5%) reported they would not be prepared to do any of these tests at home, 35 participants (88%) said they would be willing to perform one of the tests at least once a week and 21 (53%) said they would complete one of the tests every day if asked (Figure 9).

DISCUSSION

The present study indicated that children with and without eye disease were able to test their own contrast sensitivity

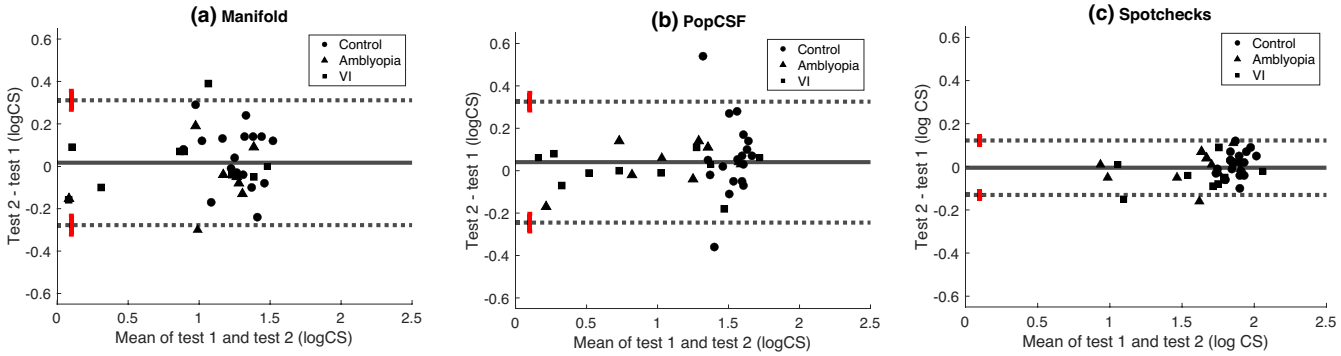

FIGURE 5 Bland–Altman plots showing the test–retest repeatability of: (a) Manifold, (b) PopCSF and (c) Spotchecks. Circles show control participants, triangles show those with amblyopia and squares show those with vision impairment (VI). The solid line indicates the mean difference. Dashed lines show the 95% limits of agreement (±1.96 standard deviation from the mean difference). Red error bars show the 95% confidence intervals on the limits of agreement.

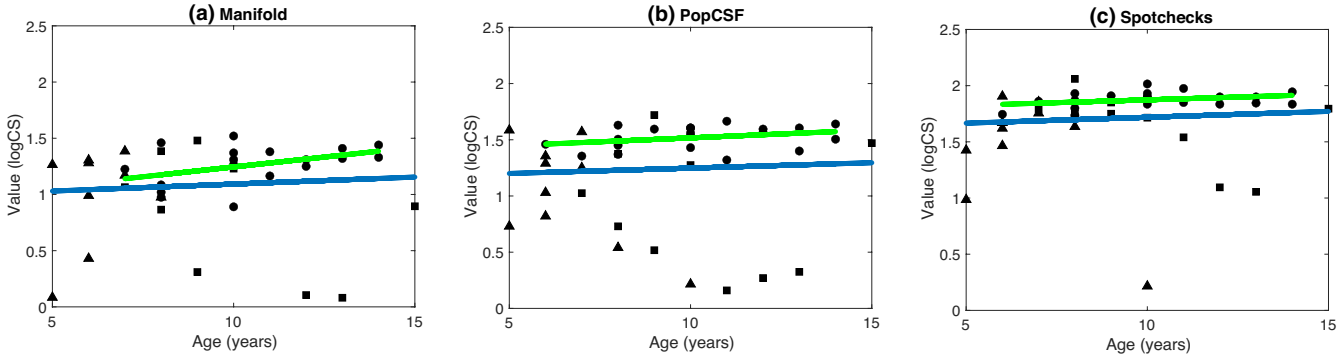

FIGURE 6 Relationship between age and contrast sensitivity (CS) measurements for all participants. Circles show control participants, triangles show those with amblyopia and squares show those with vision impairment. Blue line indicates the linear regression for all participants. Green line indicates the linear regression for control participants only.

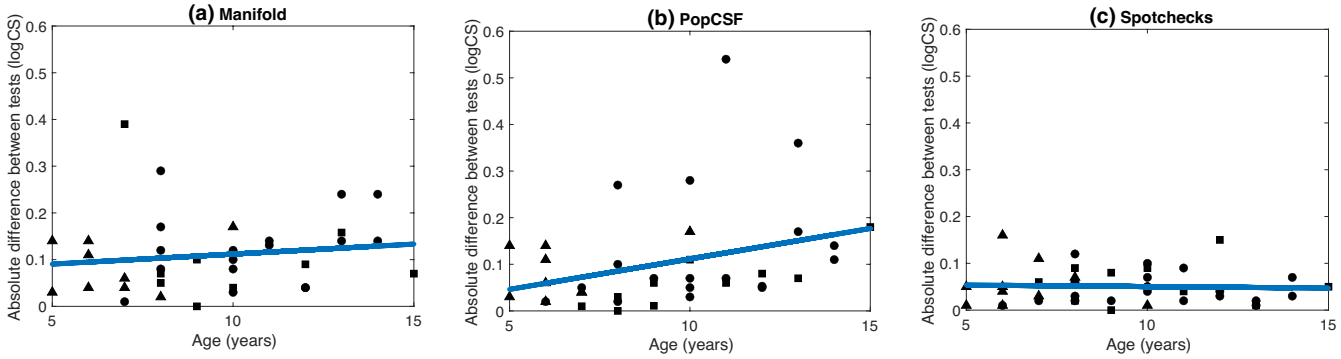

FIGURE 7 Relationship between age and the absolute difference between two tests (repeatability) for Manifold, PopCSF and Spotchecks. Circles show control participants, triangles show those with amblyopia and squares show those with vision impairment. The blue line shows the least squares linear regression, fitted across all participants. CS, contrast sensitivity.

in a clinic environment with minimal supervision. This represents an important step in determining whether children and young people can measure their own contrast sensitivity at home.

All participants completed the paper-based test, but technical errors led to some data not being collected on the digital tests. Errors experienced included one of the digital tests not working for two participants as the device was insufficiently charged and another device failing to track head position and therefore presenting stimuli having the wrong size (an error later corrected in a software update). Data were excluded for one participant in

TABLE 3 Median test time for each group of participants.

	Median (IQR) [range] test time (s)		
	Manifold	**PopCSF**	**Spotchecks**
Control	149 (17) [125–189]	148 (40) [104–232]	222 (74) [156–430]
Amblyopia	189 (48)** [144–247]	127 (19)* [105–150]	197 (134) [86–430]
Vision impairment	161 (45) [131–225]	125 (19) [106–171]	194 (104) [137–319]

Note: Asterisks show results significantly different to the control subjects for this test (Wilcoxon test, $*p < 0.05$; $**p < 0.01$).

Abbreviations: IQR, interquartile range.

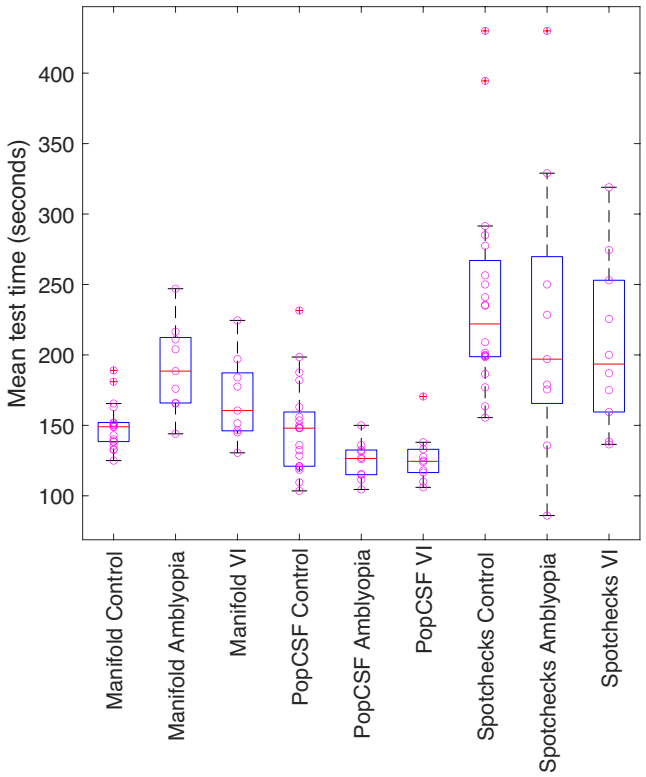

FIGURE 8 Mean test time for each test for each group of participants. Circles show the average result for each participant (mean of two tests). Red lines show group medians. Blue boxes show the 25th–75th percentile. VI, vision impairment.

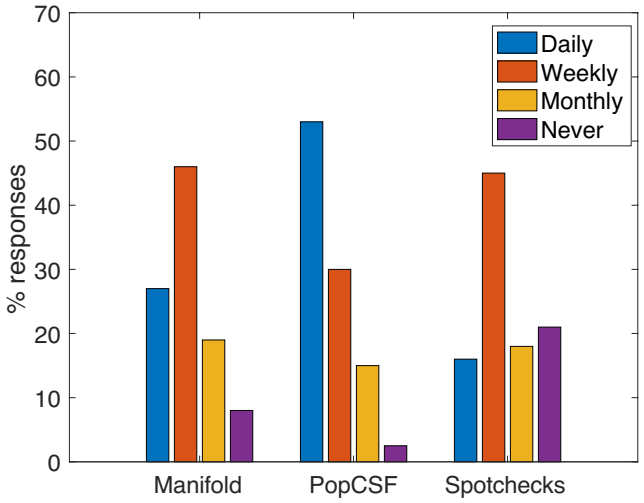

FIGURE 9 Frequency with which children said they would perform each test at home. Blue bar: every day; red bar: every week; orange bar: every month; purple bar: never.

a single test when it was discovered that she was 'peeking' with the patched eye—a problem that is not unique to digital tests, but which may prove to be challenging when children measure their own vision at home.

Contrast sensitivity as measured by the three new tests was significantly correlated with clinically measured values. This confirms previous research on the Spotchecks test for adults[25] and children,[48] as well as for adults using the Manifold test.[53]

While all three tests measured contrast sensitivity, the findings were not directly comparable. Manifold measured the area under the CSF for letter identification, PopCSF measured the area under the CSF for grating detection while Spotchecks measured the spot detection threshold for a specific point on the CSF (0.8 cycles per degree, slightly below the peak of the CSF for control subjects but closer to the peak for those with eye disease[1,54]). As the viewing distance was not fixed for Spotchecks, it is possible that the point of the CSF tested was different between participants (or within the same participant, if their viewing distance changed during a test). There were also differences in the area of the visual field measured by these tests. Manifold and Spotchecks measured contrast sensitivity in the centre of the visual field (using foveal vision in those without eye disease), whereas PopCSF measured contrast sensitivity across more of the visual field (as the targets drifted around the entire screen, which subtended around 40 degrees of visual angle). Finally, there were luminance differences between the three tests: Manifold and PopCSF are internally illuminated but have different screen luminance (102 and 274 cd/m^2, respectively), whereas Spotchecks is externally illuminated.

Despite these theoretical differences, there was a reasonable correlation between the values measured on the three tests, particularly between the two tests that measured a complete CSF (i.e., Manifold and PopCSF, Figure 4). Repeatability was good for all three tests. Bland–Altman analysis showed no evidence of proportional bias (Figure 5). Cronbach's alpha was high for all three tests ($\alpha > 0.95$), indicating excellent internal consistency. The limits of agreement showed that a difference in logCS of 0.3 log units could be detected with 95% accuracy by all three tests; a value similar to that found for young adults performing an earlier iteration of the Manifold test.[55] The repeatability values compared favourably with previously reported values for adults with[53] and without[27] eye disease using the Manifold test. For the Spotchecks test, our coefficient of variability (0.13 logCS) was remarkably similar to

the value measured by Anderson et al.[48] in a group of 43 children with good vision (0.14 logCS).

We did not find a significant effect of age on the results (Figure 6) nor test–retest variability (Figure 7). Redmayne and Russell[40] reported that the correlation between clinical and home-based tests was better in those over 8 years of age, but we did not observe this effect in our data.

Several tests exist for home monitoring of visual acuity in children.[56–58] In this study, we have chosen to look at tests that measure contrast sensitivity, as we were interested in two specific populations: children receiving treatment for amblyopia and those with other vision impairments. In amblyopes, it is known that the CSF is reduced even after treatment has restored visual acuity to normal levels.[20] In those with vision impairment, contrast sensitivity has been shown to predict visual function and disease progression. Testing the CSF generally took longer than measuring visual acuity, with each test typically taking 2–4 min per eye, but this small increase in test time was vastly outweighed by the reduction in travel and clinic waiting time. Despite the longer test time, only one of the participants (a 13-year-old boy with bilateral vision impairment) said he would not be prepared to do any of these tests at home. Visual acuity provides a quick and informative test of visual function in the clinic, but for home use, where test duration is not limited by clinician time, we suggest using the more detailed assessment of visual function offered by contrast sensitivity testing.

Nearly 90% of the participants said they would be willing to perform one of the tests at least weekly and more than half said they would complete one of the tests every day. Across all participants, the PopCSF test was the most popular, but post-hoc analysis of test preference indicated that the older participants preferred the paper-based Spotchecks test (four of the six teenagers who completed the study rated Spotchecks as their favourite and only two preferred the PopCSF test).

Agreeing to do the test should not be confused with enjoying it. In a previous evaluation of the PopCSF test, Elfadaly et al.[29] reported that 'some children remarked that the [PopCSF] was actually somewhat boring, but much less so than current eye tests'. Even if young people say that they would like to perform a test at home, they may not do so. Painter et al.[34] found that only 16% of 96 families who agreed to undertake a home vision test completed it successfully.

Strengths and limitations

Strengths of our study include the diverse range of eye diseases included, the variety of contrast sensitivity tests we had access to and the controlled environment in which we performed the tests.

One limitation of our study design was that participants were not completely unsupervised, as an investigator was present in the room for all testing. The investigator ensured that the correct eye was occluded, the test was running effectively and that the correct viewing distance was being maintained. This may be a reasonable simulation of home-based vision testing (where a parent may be present to supervise testing), but we do not know how involved parents or carers will be when children perform home-based vision testing. We anticipate that this will range widely, from the child being reminded to perform the test but being left unsupervised through to the adult looking over the child's shoulder as they respond to each individual target. Although it is difficult to measure the level of caregiver supervision,[59] it would be interesting to investigate the role of supervision on these tests when they are used at home.

The ages of our three groups were not matched, as those with amblyopia were significantly younger than the participants with good vision and vision impairment. We do not think that the age difference between disease groups has confounded our results as we did not find a relationship between age and contrast sensitivity (see Figures 6 and 7), despite children with amblyopia having lower contrast sensitivity than control subjects.

We have chosen to use the standard clinical test of letter contrast sensitivity as the gold standard for our analyses but accept that there are several limitations to this approach. All three of our novel tests measured different aspects of the CSF: Manifold and PopCSF measured the area under the CSF, but Spotchecks measured just one point on this function. Two of the tests (PopCSF and Spotchecks) measured the ability to detect a target rather than to identify it, but optotype identification was required by Manifold. Further, we used two different letter contrast sensitivity tests here: Pelli–Robson for the control participants and MARS for those with eye disease.

Many interesting questions about these tests remain unanswered. Before they can be integrated into home-based clinical practice, their usability at home should be determined, as should the optimal testing interval, the best method for collecting the data (e.g., remotely or at in-person appointments), the level of a clinically meaningful change in contrast sensitivity and the best way for monitoring compliance (e.g., that the correct eye is covered during monocular testing). It also remains unknown how willing parents would be to have an additional (expensive) device at home, whether they would be keen to allow additional 'screen-time' for their children to do these tests and how many of the devices may be stolen or lost.

CONCLUSIONS

We have shown that children aged 5–15 years are able to measure their own contrast sensitivity with minimal supervision, using tablet- or paper-based tests. The results of these tests are repeatable and correlated with standard clinical tests. Despite test times of 2–4 min per eye, most children indicated that they would be prepared to

perform these tests at home. The next phase of this study is to issue one of these tests to young people for home use. This will also enable us to compare contrast sensitivity measured in the laboratory to home-based measurements. In adults, visual acuity and contrast sensitivity is consistently better when measured in an eye clinic than when measured at home[60,61] and it will be interesting to determine whether this effect is also seen in children and young people.

AUTHOR CONTRIBUTIONS

Michael D. Crossland: Formal analysis (equal); investigation (lead); writing – original draft (lead). **Tessa M. Dekker:** Conceptualization (equal); writing – review and editing (equal). **Annegret Dahlmann-Noor:** Conceptualization (equal); writing – review and editing (equal). **Pete R. Jones:** Conceptualization (lead); formal analysis (equal); funding acquisition (lead); methodology (equal); software (lead); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Anonymised data will be available on reasonable request.

PARTICIPANT CONSENT

All participants were provided with age-appropriate details about the study and assented to participating. Written informed consent was provided by the parent or carer.

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