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ORIGINAL ARTICLE

Visual Performance and the Use of Colored Filters in Children Who Are Deaf

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ABSTRACT

Purpose. To assess visual performance and the effects of color overlays on reading in children who were deaf and children who could hear.

Methods. Thirty-one children who were deaf (mean [±SD] age, 14 [±1.99] years) and 39 children who could hear (mean [±SD] age, 13.58 [±3.09] years) underwent an optometric examination with specific emphasis on near vision. Participants chose an overlay with color optimal for clarity and comfort and completed the Wilkins Rate of Reading Test both with and without an overlay of this color. Nineteen of the participants who were deaf were retested a year later with a modified rate of reading test that used only words that can readily be signed. This modified rate of reading test was repeated 1 week after its first administration.

Results. Participants who were deaf had greater ametropia ($p = 0.003$), a more distant near point of convergence ($p = 0.002$), and reduced amplitude of accommodation ($p < 0.001$) compared with normal-hearing participants. All the children who were deaf chose a color overlay, with 45% choosing a yellow overlay, which increased the rate of reading by 18%. Only 66% of the participants who could hear chose an overlay, and it had no effect on reading speed. With the modified reading test, 7 of 19 (37%) again chose yellow. These participants showed a 9% increase in reading speed with the yellow overlay, which was repeatable 1 week later. The remainder showed no increase in rate of reading with their chosen overlay.

Conclusions. An eye examination of children who are deaf needs to include a comprehensive assessment of near visual function so that deficiencies of amplitude of accommodation, near point convergence, and ametropia can be treated. A yellow overlay improved reading speed in the participants who were deaf, whereas other colors did not, a finding at variance with earlier work on hearing populations.

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Key Words: vision, near visual function, deaf, reading, colored overlays

Children who are deaf struggle with reading attainment more commonly than children who can hear.[1,2] Learning to read involves an understanding of the relationship between letters and sound, which involves both auditory and visual cognition. Children who are deaf have auditory difficulties, but many also have significant visual deficits.

About 90% of children who are deaf are born to hearing parents who do not know signing and who often have to learn signing with their child.[3] Children who are born to hearing parents generally have greater difficulties with reading compared with those who are born to deaf parents, possibly because of the decreased interaction with signing in the home.[4] Many children who are deaf therefore enter school with a much lower linguistic base than their hearing peers. When sign language is fluent, students who are deaf learn to read and learn academic content in printed English, despite the differences from the sign language used for daily communication.[5] Relative to students who can hear, students who are deaf commonly struggle when learning to recognize words, understand vocabulary, and use comprehension strategies.[6] The average student who is deaf leaves school at age 18, with a reading age approximately equivalent to that of a 9-year-old child who can hear.[7]

Difficulties with reading acquisition in otherwise neurologically, attentionally, and intellectually normal children have often been attributed to two deficits: phonological and visual. In the hearing population, deficits in processing the phonology of language have been found to impact reading ability.[8,9] For example, individual differences in phonological awareness and

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rapid automatic naming ability have been shown to influence the rate at which children who can hear acquire early reading skills.[10] Importantly, if subtle phonological deficits are associated with poor reading in the hearing population, then the question arises as to how it is possible for profoundly deaf subjects to read.

Although phonological awareness is critical for the understanding of letter-sound relationships, the reading process actually begins with an analysis of printed patterns on the page and is intimately tied to visual perception. It is possible then to suppose that reading difficulties may be, at least partially, linked to visual processing. Martin et al.[11] have recently found that children with sensorineural hearing loss displayed reduced motor proficiency, which they suggested may impair the usual ocular motor/vestibular relationship. This in turn could affect visual stability and hence acquisition of reading.[11]

To date, no direct relationships between visual deficiencies and reading abilities in people who are deaf have been investigated, although research in normal-hearing preschoolers with significant ametropia ($\geq$+4.00 diopter sphere and $\geq$2.00 diopter astigmatism) have shown improvement in cognitive abilities when the ametropia has been corrected.[12] The lack of studies is particularly surprising given the research showing that subjects who are deaf have significant visual problems when compared with their hearing peers.[13] Refractive and binocular vision abnormalities have typically been the most commonly reported. For example, studies have shown the prevalence of hypermetropia, myopia, and astigmatism in people who are deaf to be between 18 and 39%[13] and that of binocular vision abnormalities (e.g., heterotropia) to be between 5.3 and 18%.[14]

Binocular vision dysfunction is often categorized in terms of manifest eye turns (i.e., heterotropias) or latent eye turns (i.e., heterophorias). In poor readers, inadequate or weak binocular fusion ranges at near and a more remote near point of convergence (NPC) are common.[15]

Sometimes, symptoms of visual discomfort are associated with perceptual distortion, usually of text, in which case they are referred to as visual stress.[16] Visual stress is provoked by images with high-contrast stripes such as printed text and is more common in those who have reading difficulties and binocular instability.[17] The subjects who are susceptible have found that the use of specific color overlays relieve these symptoms and increase reading speeds and visual comfort. Color overlays have also been shown to benefit other groups: patients with autism,[18] multiple sclerosis,[19] or stroke.[20] To the authors' knowledge, no study has investigated the influence of color filters on reading in a deaf population.

The present study is the first to look at the relationship between visual function and reading ability in children who are deaf by conducting a thorough assessment of visual function and rate of reading with and without color filters.

Participants

Ethics Statement

The participants were recruited from the student population attending a dedicated school for the deaf, and its partner mainstream school in the United Kingdom. All participants and parents gave written informed consent after a written and verbal explanation of the procedures involved. All procedures conformed to the tenets of the Declaration of Helsinki and were approved by the Anglia Ruskin University Ethics Committee.

A total of 33 (prelingual) participants who were deaf (11 female and 22 male participants aged 7 to 19 years; mean age, 13.6 years) were enrolled. Sixteen children were profoundly deaf (hearing loss > 90 dB; occasional loud sounds are perceived) and 17 were severely deaf (hearing loss > 70 dB unable to hear even shouted conversations).[21] Therefore, the deaf sample consisted of children who could not hear conversational speech (~60 dB) and consequently would not spontaneously learn to talk. All of the participants who were deaf were fluent British Sign Language (BSL) signers. Nonverbal intelligence quotient (IQ) was assessed with an open test that could be administered to both deaf and hearing groups: Raven's Standard Progressive Matrices.[22] A total of 41 control participants (19 female and 22 male participants aged 11 to 18 years; mean age, 14 years) were enrolled as stated above. The mean age and IQ did not differ between the groups. All control children had no known hearing problems and no other learning disability.

METHODS

Experimental procedures were performed at the schools. All optometric and IQ testing was conducted by the first author. In each school, the lighting was a combination of normal background office lighting and task lighting using an Osram Dulux 11 w 865 lamp (color temperature 6000K) with an illuminance of 300 to 500 lux operated from an electronic ballast at a frequency of 25 kHz. Testing was always performed in the same room and under the same lighting conditions. All children who were deaf had instructions communicated verbally and via BSL. The deaf school also provided an experienced BSL translator. Comprehension of the instructions for tests requiring a subjective response was inferred from correct answers to preliminary examples of the test material. PowerPoint presentations were written to aid understanding of the associated and dissociated phoria tests. The PowerPoint presentation in conjunction with verbal and signed instruction maximized compliance and accuracy of the subjective testing. All visual, binocular, accommodative, and reading tests were performed with the best-corrected refraction worn. One participant whose vision required further investigation (e.g., visual acuity <20/30 without a known cause) was directed via the participant's parents to the community optometrist for a full eye examination.

The tests were conducted in the following order.

Routine Optometric Tests

Vision and Visual Acuity

Vision (uncorrected) and visual acuity (best corrected) were measured at 3 m using a Bailey-Lovie logMAR (logarithm of the minimum angle of resolution) chart. Near monocular visual acuity was measured at 0.4 m with a reduced logMAR chart for near. The charts use a by-letter scoring system of 0.02 log units per letter correctly identified. Measures were performed monocularly and the right eye was always measured first.

Refractive Error

Refractive error was measured objectively with a Nidek AR-600A autorefractor (Nidek, Gamagori, Japan)[23] and was compared with the participant's habitual correction. A cycloplegic agent was not used as the children who were deaf were in their school environment, and reduction in visual performance, in addition to their hearing impairment, was considered unacceptable by the school. The Nidek autorefractor, using the "autoshot" and "autotracking" facilities, estimates the refractive error by averaging three successive readings in each session. The autotracking mechanism enables the machine to follow small losses of fixation by the subject. The autoshot function permits automated serial measurements when the instrument is in focus. Three readings were collected for spherical and cylindrical power and their respective averages were calculated.

Binocular Vision

Initially, a cover test with prism bar was performed to identify and measure any heterotropia.

Dissociated Phoria

Modified Thorington phoria tests (Bernell Corp, South Bend, IN) were performed at distance and near.[24] Tests were always conducted in the same order: distance horizontal phoria, distance vertical phoria, near horizontal phoria, and near vertical phoria. The Muscle Imbalance Measure Cards were used at 3 m (distance) and 0.4 m (near). The participants were instructed to look at the light in the center of the card and to keep the numbers on the card clear. A Maddox rod was placed over the participant's right eye and the number corresponding to the red line was recorded.

Associated Phoria

Fixation disparity (vertical and horizontal) was measured at distance and near using the appropriate section of the Mallet units (i.O.O. Sales Ltd, London, UK). This test is commonly used in optometric practice in the United Kingdom to assess decompensating heterophoria. A polarized visor was placed on top of the participants' correction. Any disparity was then aligned with the minimum amount of prism of appropriate base direction. Participants who reported only seeing one of the lines suggesting suppression were excluded from the fixation disparity data set.

Stereoacuity

The Randot stereo test screening plates (Stereo Optical Co Inc, Chicago, IL)[25] present disparities in the range of 500 to 250 seconds of arc and involve a simple recognition of shapes: square, circle, star, triangle, cross, and E. The Randot threshold plate presents three monocularly visible circles, one of which has disparity when viewed binocularly through the cross-polarized filters. There are 10 sets of three circles presenting a range of disparities from 400 to 20 seconds of arc, and the participants were asked to identify which circle of each set "stood out from the others." Only participants who passed the 500 seconds of arc screening plate progressed to the threshold plates.

Near Point of Convergence

Near point of convergence was measured with a RAF ruler (Haag-Streit, Harlow, UK). Participants were asked to fixate on the dot located in the center of the vertical line. The line target was positioned at the far end of the RAF rule and was then moved at about 5 cm/s along the RAF rule toward the participant. They reported when (if) the line appeared double, and the distance from the participant's cornea was noted. This was repeated three times and averaged results were recorded (in centimeters). Both deaf and hearing groups received instructions at the outset only: no additional prompting was provided during the test.

Amplitude of Accommodation

Accommodative amplitude measurements were made binocularly using a RAF ruler. The participants were required to read the N5 line of letters and instructed to keep the letters perfectly clear. The target was moved at about 5 cm/s toward the participant until they reported the first sustained blur. This point (in centimeters) was recorded. No additional instructions to clear the target were given to either group because it was not possible to instruct the deaf participants during the test. The target was then moved away until the participant reported the letters became clear. Averages of three measurements were obtained. The six measures were then averaged and converted to diopters.

Contrast Sensitivity

A Pelli-Robson chart (Haag-Streit)[26] was used to measure contrast sensitivity binocularly. The chart consists of 16 triplets of letters with each successive triplet decreasing in contrast by a factor of 0.15 log units when viewed at a distance of 1 m. The chart uses a by-letter scoring system of 0.05 log units per letter correctly identified.

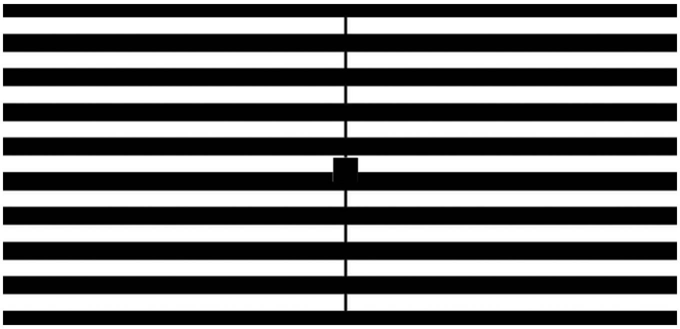
Color Vision

Color vision was assessed with the Ishihara Test (Kanehara Trading Inc, Tokyo, Japan) and the City University Test (Third Edition) (Keeler Ltd, Windsor, UK). Each plate on the 25-plate Ishihara test was viewed at 75 cm for about 4 seconds. The number of errors was noted. If a participant failed the Ishihara test (>3 errors), then the color deficiency was classified using the diagnostic plates. The City University Test was used at a distance of 35 cm. Four differing colored dots were arranged north, south, east, and west about a central test color. The participant was asked to choose a color that best matches the central one. Depending on the color chosen, the participant may have no color deficiency or tend more to protan, deutan, or tritan defect. More than two errors constituted a failure.

Tests Assessing Visual Stress

Pattern Glare Test

All participants were assessed for visual stress with a modified Pattern Glare Test (i.O.O. Sales Ltd) at 0.4 m (Fig. 1).[27] Participants were shown a grating with square-wave luminance profile, Michelson contrast about 0.9, a spatial frequency of 3 cycles per degree, circular in outline, and a radius of 13 degrees. They were asked a series of questions regarding the perceptual distortions that they experienced, each beginning "Looking into the centre of the grid that is in front of you…. Do you see any of the following? Please answer each question with either yes/no; Pain, discomfort, shadowy shapes amongst the lines, shimmering of the lines, flickering, red, green, blue, yellow, blur, bending of the lines, nausea, dizziness, unease." Each "yes" answer resulted in an additional 1 being added to the score. Hollis and Allen[28] used this technique to identify whether people are likely to benefit (in



AQ2 **FIGURE 1.**

terms of improved reading) from individually chosen color overlays. They suggested that subjects with scores of 4 or more indicate a susceptibility to visual stress.

Color Overlays and Wilkins Rate of Reading Test

The Intuitive Overlay system (i.O.O. Sales Ltd) was used. The color overlays were presented in the following order: Rose, Lime Green, Blue, Pink, Yellow, Aqua, Purple, Orange, Mint Green. This order was adopted to reduce the chances of complementary colors being placed next to each other. The top overlay (Rose) was placed to the left of the test page, covering one of the two passages of text. When the text covered by the overlay was judged preferable to the uncovered side, a second overlay was placed beside the first so that both passages of text were now covered by overlays. The child was again asked which color made the text clearer and more comfortable. The process of removing the poorer overlay and leaving the best overlay in place was continued until all the overlays had been shown. The test was conducted binocularly. Although six participants had heterotopia and associated amblyopia, binocular viewing ensured that all participants were reading text that was of a size well above that sufficient to read fluently.

The Wilkins Rate of Reading Test (WRRT) was used to measure participants' rate of reading. The test consists of a paragraph of 10 lines of text, each line comprising 15 common words arranged in different random order. Participants are required to read the paragraph aloud as quickly as possible for 1 minute. The words cannot be guessed from context because of the random order. The words are all high frequency and therefore within the sight vocabularies of most children age 7. The WRRT maximizes visual stress while minimizing the linguistic and semantic aspects of reading[29] and is reported to be reliable and valid.[29] Each of the four paragraphs of the WRRT has a different random order of words. The four paragraphs were given (1) with the chosen overlay, (2) without, (3) again without, and finally (4) with an overlay. The ABBA design was used to minimize bias from learning/fatigue effects. Most of the practice effect occurs from the first to the second administration and the ABBA design therefore biases any mean difference against a benefit. An average rate of reading with and without the overlay was calculated. The children who were deaf read and communicated using BSL.

Modified Rate of Reading Test

The WRRT was not developed for use by the deaf. Some of the words are not found within BSL and some of the participants who were deaf consequently used a generic sign for some of the words that they could not sign, for example, *it*, *and*, *to*, and *for*. This generic sign was accepted as the correct response. We therefore developed an alternative version of the test with the assistance of the BSL tutors from the school for the deaf. We used the following words, which are basic signs that are learnt at stage one BSL: *hat*, *bird*, *cake*, *sun*, *play*, *rain*, *me*, *tree*, *come*, *fish*, *read*, *book*, *car*, *ball*, and *like*. The modified test was administered 1 year after the first test and followed the same procedures as the standard WRRT. Fourteen of the participants who were deaf agreed to repeat the modified WRRT 1 week later to measure the repeatability of the modified test.

RESULTS

A total of 70 from the original cohort of 74 participants completed the full range of tests, composed of 31 deaf (20 male and 11 female) and 39 hearing (23 male and 16 female) participants. Two children who were deaf and two children who could hear changed schools and were removed from the study. The Ravens IQ (±SD) for the deaf and hearing groups were 88.7 (±11.8) and 95.4 (±30.6), respectively. The groups were well matched for age: 13.6 (±3.0) and 14 (±11.8) years. There was no significant difference in age (t_{68} = 0.70, p = 0.49) or IQ (t_{68} = 1.55, p = 0.13) between groups. Table 1 lists and summarizes the findings for both groups. T1

In the listing of the routine optometric test results that follow, the statistical tests for each comparison are presented without a Holm-Bonferroni adjustment, which would require p less than 0.004. Three remained significant with this adjustment (spherical ametropia, NPC, and amplitude of accommodation [AA]).

Routine Optometric Tests

Refractive Error

Neither group shows any significant refractive differences between right and left eyes; hence, data have been reported for the right eye in Table 1. Forty-eight percent of the participants who were deaf and 15% of the participants who could hear had a spherical ametropia of greater than or equal to 1 diopter (D) (p = 0.003, Fisher exact test). Twenty-six percent of the participants who were deaf and 5% of the children who could hear had a cylindrical error of more than 1 D (p = 0.02, Fisher exact test). Forty-five percent of the participants who were deaf wore spectacles compared with only 12.8% of the hearing group.

Visual Acuities

The visual acuities of the better eye are reported because six of the participants who were deaf were heterotropic. The mean (±SD) logMAR for the participants who were deaf was −0.01 (±0.20), and that for the hearing group was −0.06 (±0.07) (t_{68} = 1.39, p = 0.17).

Binocular Vision

Heterotropia

Six of the participants who were deaf (19%) had a heterotropia of greater than 10Δ (four in the right eye); 4 (13%) exhibited exotropia whereas 2 (6%) had esotropia (with full refractive correction). There were no vertical deviations. None of the control

TABLE 1.

Characteristics of the participants including color of overlay chosen (Overlay color), right eye spherical component (RE Sph), right eye cylindrical component (RE Cyl), heterotropia presence (H tropia), near point of convergence (NPC), amblyopia (*), AA, reading speed with color overlay (Reading speed with color), reading speed without color overlay (Reading speed without color), and percentage change in reading speed with color

RE vision (unaided logMAR)	RE Sph, D	RE Cyl, D	RE visual acuity, logMAR	RE near visual acuity, logMAR	H tropia	NPC, cm	AA, D	Overlay color	Reading speed with color, words per minute	Reading speed without color, words per minute	Percentage change in reading speed	Pattern glare
Deaf												
0.04	0.25	−0.30	0.04	−0.20		7	10.20	Yellow	65.0	74	−12	0
−0.10	0.25	−0.30	−0.20	−0.24		14	6.90	Yellow	64.5	60.5	7	2
0.30*	2.75	−1.30	0.30	0.40	Y		8.80	Yellow	84.5	84	1	0
−0.24	0.75	−0.50	−0.24	−0.24		7	11.10	Yellow	103.0	89	16	0
1.40	−3.25	−2.30	−0.04	0.02	Y		14.30	Yellow	85.0	60	42	0
0.60	−1.75	−0.30	−0.10	0.02		15	5.10	Yellow	120.0	104	15	2
0.44	−1.75	−0.30	−0.06	0.04		8	9.80	Yellow	88.0	72	22	0
0.12	0.75	−0.50	0.02	−0.04		6	9.80	Yellow	118.5	103	15	1
1.00*	−1.75	−0.50	0.80	0.70	Y		7.50	Yellow	31.5	24	31	2
0.50*	−1.25	−1.50	0.30	0.30			10.00	Yellow	71.5	53.5	34	1
0.20	2.50	−4.50	−0.02	0.00		13	9.00	Yellow	103.5	92.5	12	3
0.06	1.75	−1.00	−0.06	0.02		16	6.10	Yellow	86.5	52.5	65	0
0.04	2.00	−0.50	−0.10	−0.12	Y	10	7.90	Yellow	68.0	66.5	2	0
0.50	7.75	−2.30	0.10	−0.14		9	6.50	Yellow	150.0	150	0	1
−0.06	−0.25	−0.50	−0.04	−0.24		9	10.50	Aqua	82.5	88	−6	0
−0.02	1.75	0.00	−0.04	−0.12		13	11.10	Aqua	150	150	0	1
0.18	2.00	−2.50	0.18	0.02		10	11.10	Aqua	59.5	57	4	2
−0.18	−0.25	−1.30	−0.20	−0.24		8	12.50	Aqua	70	68	3	0
−0.10	0.25	−0.50	−0.10	−0.10		38	6.00	Blue	72.5	75.5	−4	2
0.12	1.00	−0.30	0.04	−0.02	Y		14.30	Lime green	90	81	11	2
0.06	0.25	−0.50	0.06	−0.24		8	6.40	Mint green	106	117.5	−10	2
−0.10	0.25	−0.30	−0.12	−0.16		16	6.40	Mint green	109.5	107	2	2
0.00	0.75	−0.50	0.00	−0.26		10	10.50	Rose	121.5	150	−19	1
−0.20	0.25	−0.50	−0.20	−0.14		9	10.50	Rose	147.5	120.5	22	0
−0.02	−0.25	−0.30	−0.10	0.20		6	8.30	Pink	65	74	−12	2
−0.04	0.50	−0.50	−0.06	0.02		6	9.70	Pink	100.5	108	−7	2
0.10	0.25	−0.30	0.10	−0.14		8	10.00	Pink	120	107	12	3
0.30	−1.00	−0.30	−0.10	0.04	Y		10.30	Pink	93	81.5	14	1
0.04	2.25	−0.50	−0.18	−0.10		9	7.00	Pink	56.5	41	38	0
−0.16	0.00	−0.30	−0.16	−0.10		12	11.50	Orange	150	150	0	2
−0.04	−0.25	−0.30	−0.04	−0.16		14	8.60	Orange	123.5	129.5	−5	3
Hearing												
1.00	−2.88	−3.00	−0.10	−0.20		6	11.10	No color	150	150	0	0
−0.10	−0.25	−0.25	−0.10	−0.24		6	11.10	No color	126	127	−1	2
−0.10	0.25	0.50	−0.10	−0.20		6	10.90	No color	130.5	120.5	8	1
0.10	−0.63	0.00	−0.10	−0.16		6	11.10	No color	150	150	0	2
−0.06	−0.25	−0.25	−0.06	−0.20		9	11.10	No color	150	150	0	1
0.00	−0.38	0.00	0.00	−0.14		6	10.90	No color	122	138	−12	1
0.00	−0.13	0.25	0.00	−0.20		6	11.80	No color	150	150	0	0
−0.02	0.13	0.25	−0.02	−0.10		6	10.90	No color	123	111.5	10	0
−0.02	−0.50	−0.25	−0.02	−0.02		7	10.90	No color	103.5	105	−1	2
−0.16	−0.88	0.00	−0.20	−0.22		7	11.10	No color	150	150	0	0
0.14	−0.63	−0.50	0.14	−0.14		6	12.50	No color	75	77.5	−3	1
−0.14	−0.38	−0.25	−0.14	−0.22		6	11.30	No color	145	145	0	2
1.00	−3.63	−4.00	0.00	−0.20		6	13.30	No color	114.5	126	−9	2
−0.10	0.00	−0.30	−0.10	−0.20		6	10.30	Aqua	147.5	148.5	−1	1
−0.16	−0.25	−0.30	−0.16	−0.20		6	10.90	Aqua	110	108.5	1	1
−0.12	0.00	0.00	−0.12	−0.16		6	11.10	Aqua	150	150	0	0
0.06	0.25	−0.80	0.06	0.00		8	9.80	Aqua	87	90.5	−4	1

(continued on next page)

TABLE 1.

(Continued)

RE vision (unaided logMAR)	RE Sph, D	RE Cyl, D	RE visual acuity, logMAR	RE near visual acuity, logMAR	H tropia	NPC, cm	AA, D	Overlay color	Reading speed with color, words per minute	Reading speed without color, words per minute	Percentage change in reading speed	Pattern glare
0.02	−0.25	−0.50	0.00	−0.10		6	11.50	Aqua	123.5	118.5	4	2
0.90	−2.25	−0.50	0.00	−0.12		6	13.30	Blue	150	150	0	1
−0.16	0.00	−0.30	−0.16	−0.22		6	10.70	Blue	130	118.5	10	0
−0.14	−0.25	0.00	−0.14	−0.20		6	11.10	Blue	141.5	146.5	−3	2
−0.06	−0.25	−0.80	−0.06	−0.10		7	12.50	Blue	139	129.5	7	1
0.00	0.00	0.00	0.00	−0.14		8	11.10	Blue	135	130	4	1
0.04	−0.50	−0.30	0.00	−0.10		6	11.10	Blue	111	125.5	−12	0
0.04	0.00	−0.30	0.04	0.12		6	9.20	Blue	143	126.5	13	0
−0.16	−0.25	−0.30	−0.16	−0.20		6	10.90	Blue	99	91.5	8	1
−0.16	0.00	−0.50	−0.16	−0.24		6	12.50	Lime green	150	150	0	2
−0.12	0.50	−0.30	−0.12	−0.20		7	11.10	Lime green	150	150	0	1
−0.10	−0.25	0.00	−0.10	−0.20		6	11.80	Mint green	150	150	0	2
1.10	−2.75	−0.30	−0.04	−0.10		9	10.50	Mint green	125.5	123.5	2	1
0.12	−0.50	−0.50	−0.02	−0.08		9	8.60	Mint green	111	121.5	−9	1
−0.06	0.00	−0.50	−0.06	−0.14		10	10.50	Mint green	132	136.5	−3	1
−0.06	0.25	−0.30	−0.06	−0.16		6	11.50	Mint green	126.5	117	8	0
0.40	−1.25	−0.30	0.04	0.06		7	10.50	Pink	142.5	150	−5	1
−0.04	0.00	−0.50	−0.04	−0.20		6	10.90	Pink	120	119.5	0	2
0.30	−0.75	−0.30	0.00	−0.12		8	11.10	Pink	97	88	10	2
0.00	0.00	−0.50	0.00	−0.12		8	11.50	Orange	139	129.5	7	1
1.40	−5.00	−0.80	0.00	0.00		6	10.70	Purple	124	123	1	1
−0.10	0.25	−0.50	−0.10	−0.22		6	15.40	Gray	150	150	0	0

participants had a heterotropia. Heterotropia was more common in the participants who were deaf (p = 0.005, Fisher exact test).

Dissociated Heterophoria

Dissociated heterophoria was assessed in 24 participants who are deaf: those without heterotropia (6) and amblyopia (1) and in all the participants who can hear (39).

Distance Exophoria

Ten (42%) participants from the deaf group had exophoria ranging from 1.00 to 5.00Δ (mean [±SD], 2.50Δ [±1.33Δ]). Five (13%) of the children who could hear exhibited exophoria for distance, ranging from 0.50 to 1.00Δ (mean [±SD], 0.80Δ [±0.27Δ]) (t_{13} = 2.77, p = 0.02).

Distance Esophoria

Five (21%) participants from the deaf group exhibited distance esophoria (SOP) at distance, as well as 3 (8%) hearing participants. In the participants who were deaf, SOP ranged from 1.00 to 2.00Δ (mean [±SD], 1.70Δ [±0.48Δ]). In the hearing group, SOP ranged from 0.50 to 6.00Δ (mean [±SD], 2.50Δ [±3.04Δ]) (t_6 = 0.61, p = 0.56).

Near Exophoria

Thirteen (54%) participants who were deaf and 13 (33%) from the hearing group showed manifest dissociated heterophoria at near. In the deaf group, near exophoria ranged from 1.00 to 14.00Δ (mean [±SD], 4.92Δ [±3.77Δ]), and in the hearing group, it ranged from 0.50 to 9.00Δ (mean [±SD], 3.42Δ [±2.55Δ]) (t_{24} = 1.12, p = 0.25).

Near Esophoria

Four (17%) from the deaf group showed near esophoria, which ranged from 2.00 to 3.00Δ (mean [±SD], 2.25Δ [±0.50Δ]). None of the participants who could hear had near esophoria (p = 0.03).

Hyperphoria and Hypophoria

Five (21%) of the participants who were deaf and none of the control group exhibited vertical phoria (p = 0.01, Fisher exact test): three exhibited hyperphoria and two exhibited hypophoria of the right eye. Hyperphorias of 0.50Δ are regarded as clinically significant.[30]

Associated Heterophoria

All participants with binocular vision (excluding those with heterotropia) had associated phorias within normal limits (±2Δ).[30]

Stereoacuity

Only 25 (81%) of the participants who were deaf (those without amblyopic heterotropia but including the 1 participant who was deaf with nonstrabismic amblyopia) could perceive the 500″ target, whereas all the hearing participants could do so. The mean (±SD) stereoacuity for the deaf group was 49 (±19) seconds of arc, and that for the hearing group was 41 (±16) seconds of arc (t_{26} = 2.10, p =0.05). If the heterotropic participants are included in the analysis,

TABLE 2.
Reading speed of the deaf and hearing groups with and without their chosen overlay

Groups	Words per minute without color overlay	Words per minute with color overlay
Deaf, yellow (n = 14)	77.5 ± 30.2	88.5 ± 29.4
Deaf, nonyellow (n = 17)	101.0 ± 31.3	100.3 ± 33.3
Hearing, color (n = 27)	130.9 ± 18.5	129.5 ± 19.5
Hearing, no color (n = 12)	129.2 ± 22.8	128.29 ± 23.1

Note that all participants in the deaf group chose a color overlay.

then the children who were deaf have significantly lower stereopsis than their hearing peers (t_{31} = 3.65, p = 0.001).

Near Point of Convergence

Near points of convergence averaged only 11.3 (±6.4) cm in the deaf group and 6.7 (±1.1) cm in the hearing group. The NPCs were more remote in the deaf group (t_{62} = 4.38, p = 0.002).

Amplitude of Accommodation

The AA averaged 9.3 (±2.3) D for the deaf group and 11.2 (±1.1) D for the hearing group (t_{68} = 4.58, $p < 0.001$). A significant correlation between NPC and AA for the participants who were deaf was found (r_s = 0.45, p = 0.03), whereas the hearing participants showed little correlation (r_s = 0.23, p = 0.16). These correlations may have reflected the binocular nature of both measurements.

Contrast Sensitivity

There was no difference in contrast sensitivity between the deaf group (mean [±SD], 2.05 [±0.10] log units) and the hearing group (mean [±SD], 2.08 [±0.04]; t_{68} = 1.38, p = 0.17).

Color Vision

No color deficiencies were found in either group.

In summary, the optometric examination of the deaf group revealed a high prevalence of heterotropia, greater ametropia, more remote NPC, and reduced AA. These impairments could compromise reading.

Tests Assessing Visual Stress

Color Overlays

All participants who were deaf chose a color overlay as improving the clarity of text, yellow being the most popular choice (14 of 31, or 45%; Table 1). None of the children who could hear chose yellow and 33% preferred no overlay. When the children in the hearing group opted for an overlay, a blue overlay was found to be the most popular choice (6 of 39, or 20%). There was no link between refractive error and color chosen by the deaf group; the mean spherical equivalent of the participants that chose yellow was similar to that of those that chose other colors (t_{29} = 0.15, p = 0.88).

Rate of Reading

The rates of reading for each group, with and without color overlays, are shown in Table 2. The children who were deaf signed the words, and not surprisingly, they did so more slowly than participants who could hear both with ($t_{46.0}$ = 5.5, p = 0.001) and without overlays ($t_{46.9}$ = 5.8, p = 0.001). Children who were deaf who chose yellow increased their reading speed by an average of 18% (t_{13} = 3.7, p = 0.003). Those who chose a different color increased by only 3% on average, which was not significant. The children who chose yellow increased their reading speed by significantly more than the children who chose the remaining colors (t_{29} = 2.4, p = 0.02). There was no significant change in reading speed for those hearing participants who chose a color (t_{37} = 0.10, p = 0.33).

Modified Rate of Reading Test

One year later, 19 children who were deaf from the original sample were available for retest (9 female and 10 male participants, 12 to 19 years). This group included 4 participants who had heterotropia and associated amblyopia. The overlay selection procedure was repeated and the reading rate with and without the chosen overlay was compared, as before, in an ABBA design. Of the 14 children who originally chose a yellow overlay, 9 were available at retest and 5 chose yellow on the second occasion. An additional 2 children now chose a yellow overlay. The average reading rate with and without a yellow overlay and overlays of other colors is shown in Table 3.

The reading rate was higher with the yellow overlay than without (t_{17} = 2.3, p = 0.01). The increase in reading speed with a yellow overlay was associated with a decrease in errors from an average of 1.7 to 1.1 (t = 2.0, $p < 0.05$). There was no difference in reading speed or errors with overlays of other colors. The repeatability of the modified WRRT was good (r = 0.86; $p < 0.001$).

Pattern Glare

There were no differences between groups. Only two participants (who were both deaf) scored more than two symptoms (Table 1), which is still below Hollis and Allen's[28] suggested threshold for visual stress.

DISCUSSION

In studies that have spanned 80 years, children who are deaf have consistently exhibited greater visual difficulties than their hearing peers, presenting with both optometric and ophthalmological problems. Previous research has demonstrated increased levels of refractive, binocular, and pathological problems in

TABLE 3.
Reading speed of participants who were deaf with the new WRRT separated according to their choice of overlay color

	Words per minute without overlay	Words per minute with overlay
Yellow (n = 7)	76.9 ± 34.6	83.9 ± 26.9
Nonyellow (n = 12)	80.6 ± 18.7	78.8 ± 21.3

children who are both severely and profoundly deaf (for a review, see Hollingsworth et al.[14]). The current study has also found marginally increased levels of ametropia in the participants who were deaf: nearly half were prescribed spectacles compared with 15% of the hearing control subjects, although the levels of ametropia were not as great as previously found.[13] It was not possible to undertake cycloplegic refraction because of disruption to teaching; thus, the present findings may underestimate the degree of hypermetropia. In the school used for this study, only one child had uncorrected ametropia to a level where, for the first time, spectacles were necessary. This is encouraging because visual screening in children who are deaf has previously been a rarity.[14]

Previous research has shown profoundly and severely deaf subjects to have a high incidence of binocular vision anomalies such as heterotropia.[14] There were 6 of 31 participants with heterotropia in the deaf group and none in the control group. In the remaining 25 without heterotropia, associated heterophoria did not differ between the deaf and hearing groups, which is consistent with previous research in subjects with reading difficulties that has found little association between heterophoria and reading difficulties.[31] Nevertheless, children who were deaf showed a more distant NPC, weakly associated with a reduced AA, a finding not hitherto reported. These visual and binocular deficits are often found in children with poor reading skills[32] and may contribute to a reduction in reading performance.[33] These findings are commonly reported in children who benefit from the use of color overlays when reading.[34,35] It should be noted that the participants who were deaf were children attending a school for the deaf and were not specifically screened for reading disabilities.

Visualization of the written word is the starting point for reading, and the impairments found here may have significant implications for reading acquisition, particularly in children whose phonological ability is compromised by deafness.[2] Although phonological processing has been widely accepted as responsible for reading difficulties in both deaf and hearing children, visual problems have also been suggested as one of the possible causes of difficulties with reading.

Both the visualization of the written word and the acquisition of phonology are important in the development of reading skill.[36] Our results suggest that children who were deaf were impaired with respect to both the visual and phonological skills necessary for reading acquisition, despite age-normal scores on the Raven IQ test. Various groups of children with learning difficulties have been shown to benefit from the use of color overlays.[37] They tend to report pattern glare.[27] Their reading speed on the WRRT improves with the use of an overlay[38] but only when the overlay has a color previously chosen as optimal for clarity, and the optimal color differs from one subject to another. In this study, the participants who were deaf differed from previous groups in that few reported pattern glare and nearly half chose a yellow overlay. When chosen, only this color overlay increased reading speed. Overlays of other colors did not. Relatively few (26 of 39) participants with normal hearing chose a color overlay and the chosen color did not increase the rate of reading. On retesting the participants who were deaf with the modified rate of reading test, yellow was the most popular choice of overlay and resulted in an increase in reading speed. Although the number of words read per minute with the modified WRRT was reduced compared with the original, this reflects the greater accuracy of the modified test. Signing with the original test, participants who were deaf could combine words, for example, *look up*, which can be signed in one movement. Other words such as *it*, *and*, *to*, and *for* have no direct equivalent in BSL, and a generic gesture was accepted as the correct response. These gestures were quick sideways movements of the thumb and are consequently much faster than a sign such as *hat* where the hand is placed above the head. Therefore, in the modified test, every word had a unique meaning enabling the participants to sign each of the words in an unambiguous fashion.

In a sample of 39 children in mainstream education, one would have anticipated that only 2 would substantially improve their reading speed with an overlay of their chosen color.[39] It is therefore unsurprising that the hearing group showed no overall benefit from color. None of hearing group had clinically significant pattern glare, which has been shown to indicate a benefit from color in normal groups.[28]

In children with normal hearing, the choice of color overlay is very variable, and yellow is chosen by less than 10% of children who chose overlays.[40] If the children chose a color overlay, they generally demonstrate improvements in reading rate with their chosen color.[39] The deaf group were atypical in two respects: (1) they consistently chose a yellow overlay and (2) they improved their reading speed only when the choice of color was yellow.

Ray et al.[41] have shown that, in dyslexia, NPC and AA are improved with the application of yellow filters. They also showed that yellow filters improved reading ability over 3 months in their sample of dyslexic children and attributed these benefits to the effect of yellow filters on the magnocellular system. Magnocellular deficits have been reported not only in dyslexic subjects but also in deaf groups.[42,43] Although the spatial resolution of the magnocellular system is poor, it has been argued that magnocellular function is important for the perception of text.[44] However, the role and function of the magnocellular system in reading are controversial[45] and there may be little consistency from one putative magnocellular function to another.[46] It should be noted that we failed to show any association between the benefit in reading speed from a yellow overlay and either NPC or AA.

CONCLUSIONS

The findings from this study show that the participants who were deaf had greater ametropia, reduced AA, and a more distal NPC. Moreover, the participants who were deaf had a lower rate of reading, which was sometimes improved with an individually chosen overlay. This improvement was greatest when a yellow overlay was chosen. This intriguing finding was not associated with accommodation or convergence deficits and deserves further investigation. Children who are deaf are doubly disadvantaged in reading by both reduced visual and phonological skills, notwithstanding their normal intelligence. Considering the dependence these children have on vision for learning, any visual deficit needs investigation and prompt intervention.

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