Deaf and hearing children: a comparison of peripheral vision development

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Abstract

This study investigated peripheral vision (at least 30° eccentric to fixation) development in profoundly deaf children without cochlear implantation, and compared this to age-matched hearing controls as well as to deaf and hearing adult data. Deaf and hearing children between the ages of 5 and 15 years were assessed using a new, specifically paediatric designed method of static perimetry. The deaf group (N = 25) were 14 females and 11 males, mean age 9.92 years (range 5–15 years). The hearing group (N = 64) were 34 females, 30 males, mean age 9.13 years (range 5–15 years). All participants had good visual acuity in both eyes (< 0.20 LogMAR). Accuracy of detection and reaction time to briefly presented LED stimuli of three light intensities, at eccentricities between 30° and 85° were measured while fixation was maintained to a central target. The study found reduced peripheral vision in deaf children between 5 and 10 years of age. Deaf children (aged 5–10 years) showed slower reaction times to all stimuli and reduced ability to detect and accurately report dim stimuli in the far periphery. Deaf children performed equally to hearing children aged 11–12 years. Deaf adolescents aged 13–15 years demonstrated faster reaction times to all peripheral stimuli in comparison to hearing controls. Adolescent results were consistent with deaf and hearing adult performances wherein deaf adults also showed significantly faster reaction times than hearing controls. Peripheral vision performance on this task was found to reach adult-like levels of maturity in deaf and hearing children, both in reaction time and accuracy of detection at the age of 11–12 years.

Introduction

Early perceptual deprivation is known to induce neural reorganization by way of adaptation to the altered sensory experience. ‘The compensatory theory’ hypothesizes that loss of one sense may effect a sensory enhancement in the remaining modalities (Neville & Bavelier, 2002). The theory is supported by studies that have found a peripheral vision advantage in deaf adults using a range of visual tasks. In such tasks the individual is asked to fix his or her gaze to a central point while detecting a visual change in non-central vision. Deaf adults have demonstrated a superior ability both in locating a peripheral visual change and also in the rapidity of reporting it. For example, Loke and Song (1991) reported that deaf adults were faster than hearing at detecting a luminance increment in the periphery; Bosworth and Dobkins (2002) showed a motion processing advantage for deaf adults in the peripheral rather than the central field; Neville and Lawson (1987) found deaf adults to be faster and more accurate at discriminating a change in position of an apparent motion target peripherally. Additionally, Stivalet, Moreno, Richard, Barraud and Raphael (1998) reported a greater efficiency of visual search in deaf adults; Proksch and Bavelier (2002) reported deaf to have a significantly greater visual attention capacity in the periphery; Parasnis and Samar (1985) reported deaf adults faster at redirecting their visual attention toward the correct peripheral location when initially cued incorrectly. Stevens and Neville (2006) and Buckley, Codina, Bhardwaj and Pascalis (2010) reported that deaf adults detected a fine kinetic light stimulus at further peripheral locations than hearing controls. Colmenero, Catena, Fuentes and Ramos (2004) demonstrated that deaf individuals were faster at reorienting their attention to a presented target than hearing controls. Chen, Zhang and Zhou (2006) reported that deaf adult participants were 59 milliseconds faster at detecting both cued and uncued peripheral visual targets compared to hearing controls. Colmenero, Catena, Fuentes and Ramos (2004) demonstrated that deaf individuals were faster at reorienting their attention to a presented target than hearing controls. It has also been demonstrated that the neural recruitment of deaf adults to peripheral visual stimuli is increased in comparison with hearing adults. Bavelier, Tomann, Hutton, Mitchell, Corina, Liu and Neville (2000) and Bavelier, Brozinsky, Tomann, Mitchell, Neville and Liu (2001) found a larger recruitment of motion selective area MT-MST under peripheral
attention in the deaf than in the hearing adults in an fMRI study, and Armstrong, Neville, Hillyard and Mitchell (2002) found that N1 amplitudes produced in deaf adults in response to peripheral motion stimuli were significantly larger than in hearing adults.

Where central vision is considered, and individuals are asked to discriminate a visual change foveally, congenitally deaf adults have shown equal visual ability to hearing adults (Bross & Sauerwein, 1980; Poizner & Tallal, 1987; Bross, 1979; Finney & Dobkins, 2001; Hartung, 1970). These central vision tasks have included measures such as temporal resolution, brightness discrimination, contrast sensitivity, identification of unfamiliar characteristics and texture segmentation. Bavelier, Dye and Hauser (2006), in a comprehensive review paper, suggested that the specific visual enhancements observed in the deaf may be mediated by the mechanism of attention. Altered visual spatial attention may indeed explain several studies which compare central versus peripheral distractibility in deaf and hearing individuals. These studies have found that whereas hearing individuals show greater distractibility for centrally presented distracters, deaf show the opposite pattern, being able to give more attention to the visual periphery and ignore central distracters more effectively than hearing controls (Proksch & Bavelier, 2002; Bosworth & Dobkins, 2002).

It is important to note that the term peripheral vision used in the literature is ambiguous and may refer to an area of vision less than 1° to as much as 100° peripheral to a point of fixation. The aforementioned reports of peripheral vision therefore refer to a widely varying visual assessment area and typically presented visual stimuli on a computer monitor while the participant fixated a central target, with between 3° and 18° of eccentricity tested. Thus a relatively small portion of the entire field of peripheral vision has been tested by the majority of the literature. When the further peripheral field of vision (up to 100°) is considered, Stevens and Neville (2006), using Octopus perimetry, and Buckley et al. (2010) using Goldmann perimetry, found substantial increase compared to hearing controls in the peripheral visual field area within which profoundly deaf adults could detect a kinetic stimulus.

Attentional changes which particularly resource visual conditions in which a hearing person would usually benefit from simultaneous auditory and visual stimuli may influence the increased peripheral visual performance observed in deaf individuals. Indeed, an uncued stimulus which quickly appears in the periphery requires a high attentional component for its detection (Montagna, Pestilli & Carrasco, 2009). Many real-life stimuli which quickly appear in the visual periphery, for example a bus approaching from behind, provide both auditory and visual signals of approach. Deaf adults may possess increased peripheral attention for detecting such uncued stimuli in the visual periphery.

The enhanced peripheral vision attention found in deaf adults is supported by neural imaging studies which have documented increased cortical responses to peripheral vision in deaf individuals. Neville and Lawson (1987) reported that ERPs from deaf adults displayed attention-related increases in the visual cortex several times larger than hearing subjects and different in distribution when attending to peripherally presented visual stimuli. In addition to this, profoundly deaf individuals have demonstrated increased neural responses to vision from the auditory cortex (Finney, Fine & Dobkins, 2001; Nishimura, Hashikawa, Doi, Iwaki, Watanabe, Kusuoaka, Nishimura & Kubo, 1999). Fine, Finney, Boynton and Dobkins (2005) identified a consistent auditory cortex response to visual stimuli in deaf subjects, not present in hearing controls, and this cortical plasticity has been found to occur only in profoundly deaf and not moderately deaf adults (Lambertz, Gizewski, de Greiff & Forsting, 2005).

Whereas a deaf superiority in peripheral vision is largely accepted for congenitally and profoundly deaf adults within the published literature, a vastly different picture is presented from studies which have addressed vision in deaf children. Reports of normative values for vision in deaf children are few, likely because the majority of the existing literature concentrates on deaf children who have visual impairments associated with their deafness. In fact, the percentage of deaf children reported to have associated visual impairments is high, estimated to be between 33% and 60% of all deaf children (Suchman, 1967, Fillman, 1987, Regenbogen & Godel, 1985). Therefore deafness without associated vision impairment may actually be the minority group amongst the deaf. Myklebust (1964), in a psychological review of deafness, reported decreased visual ability in deaf children and proposed that acoustic deprivation may have led to inferiority in all remaining senses. Further evidence for decreased visual ability in deaf children is found in reports from Quittner, Smith, Osberger, Mitchell and Katz (1994) who studied children aged 6–13 and Smith, Quittner, Miyamoto and Osberger (1998) who studied a large group of similarly aged children, and both reported that deaf children had significantly more difficulty and required more time to discriminate a visual target event from other visual events. Netelenbos and Savelbergh (2003) reported that deaf children aged 5–7 years were slower to localize peripheral targets and deaf children aged 10–12 years were again slower than hearing controls, but the difference was smaller between deaf and hearing children in the older age group. However, Parasnis, Samar, Bettger and Sathe (1996), in a study of 12 Indian deaf children, and Thorpe, Ashmead and Rothpletz (2002), who studied only nine deaf children without cochlear implants, were unable to replicate the above findings. Interestingly, Thorpe et al. (2002) reported a significant correlation of age and non-verbal intelligence with visual attention performance but no significant effect of deafness on performance. However, the above studies did not isolate the function of peripheral vision, rather testing visual search ability and visual attention performance.
Peripheral vision in deaf and hearing children

Rettenbach, Diller and Sireteanu (1999) compared texture segmentation and visual search ability in both profoundly deaf juvenile and adult subjects (aged 6–20 years) with hearing controls and found that deaf children were deficient in these specific aspects of visual ability, but that deaf adults in attention-dependent conditions were more efficient than hearing controls. Netelenbos and Savelbergh (2003), as reported above, found deaf children less efficient on their visual search task than hearing controls. Corina, Kritchevsky and Bellugi (1992) and Parasnis and Samar (1985) reported superior motion detection in young deaf adults aged 18–20 years old and Rettenbach et al. (1999) also demonstrated superior visual search and texture segmentation in young deaf adults, not present in deaf adolescents.

Concerning peripheral vision specifically in profoundly deaf children, Dye, Hauser and Bavelier (2009) recently published their findings from a large group of deaf and hearing children between the ages of 7 and 17 years using the Useful Field of View task, modified to be suitable for children. The authors reported that deaf children’s performance was significantly enhanced on the task, but only after 11 years of age. In fact, in the 7–10-year age group tested in the study, deaf children performed minimally worse than their hearing peers, but this difference was insignificant. Deaf children in the 11–13 age group demonstrated significantly lower stimulus duration thresholds than their hearing peers, and deaf performance was again seen to improve in the 14–17 age group. Dye et al. (2009) also tested adult hearing and deaf populations, finding a similar performance enhancement in the deaf adults in the study, thus addressing previously conflicting reports of visual performance deficiency in deaf children and specific visual enhancement in deaf adults.

Considering the development of peripheral vision in hearing infants and children, conflicting evidence from behavioural and morphological analyses leaves maturation of peripheral vision from infancy to adulthood still to be fully understood. For example, infants have shown greater spatial resolution for visual stimuli presented centrally over peripherally (Atkinson, Braddick & Moor, 1977; Allen, Curcio & Kalina, 1989; Sireteanu, Fronius & Constantinescu, 1994; Spinelli, Pirchio & Sandini, 1998), yet on examination the peripheral retina has centrally over peripherally (Atkinson, Braddick & Moar, 1977; Allen, Curcio & Kalina, 1989; Sireteanu, Fronius & Constantinescu, 1994; Spinelli, Pirchio & Sandini, 1998), yet on examination the peripheral retina has markedly adapted these measures for paediatric use. The influence of conceptual factors (Whitehead, 1976) and concentration on peripheral vision tests is significant and may differentially influence results depending on the level of difficulty required for the test used. The tests have also varied tremendously in terms of whether stimuli presented were kinetic or static, the area of eccentricity measured within, intensity of stimuli used and length of test which is an important factor where children’s concentration levels are considered.

The test used in this study was specifically designed for both hearing and deaf paediatric populations and therefore has attempted to measure peripheral vision maturity to adult-like level across a broad range of ages by minimizing conceptual factors. Dye et al. (2009) helpfully modified the useful field of view task for the deaf and hearing children tested in their study; however, stimuli were presented only 20° of eccentricity from the point of central fixation. Therefore, while adult-like far peripheral vision in hearing children has been much debated, it is thus far unstudied in deaf children. This study presents new data from stimuli presented between 30° and 85° eccentric to central fixation, and using a range of luminances to compare deaf and hearing children and adults. The hypothesis that deaf children would underperform compared to hearing children was tested, but with the expectation that the difference between deaf and hearing children would diminish as the children matured with a possible superiority in deaf adolescents, consistent with reports of enhanced deaf adult peripheral vision.

Methods

Participants

Children with any degree of myopia were excluded, as even small degrees of myopia have been shown to significantly decrease visual sensitivity in the peripheral visual field (Koller, Haas, Zulauf, Koerner & Mojon, 2001), as well as hypermetropia greater than +2.00DS and no glasses were worn during testing as frames would have interfered with detection of peripheral stimuli. Inclusion criteria for all groups were: good visual acuity in either eye unaided or with refractive correction, minimum 0.200 LogMAR units (equivalent to 6/9.5 Snellen acuity) as assessed by crowded LogMAR testing; absence of epilepsy, and no known ophthalmological history given on parental consent and information. The number of deaf and hearing children tested and entered to the study at each age interval is given in Table 1.

Deaf children were recruited from and tested at seven schools in Sheffield, UK and the surrounding area.

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Forty-four deaf children were tested, and 25 children’s data were used in this study. Ethical approval was obtained from the University of Sheffield Ethics Committee prior to the study. The deaf group (N = 25) were 14 females and 11 males, mean age 9.92 years (range 5–15 years). All deaf children had received their diagnosis of deafness within the first 2 years of life. Nineteen deaf children’s data were rejected largely due to refractive error greater than that specified above (N = 8) or associated visual impairments observed at testing (N = 6), which included one deaf child who was found to have a previously undiagnosed bitemporal hemianopia, three children with amblyopia, one child with albinism, and one child with Usher’s syndrome. Other reasons deaf children’s data were not entered into the study were one child had cerebral palsy, two children had motor dysfunction, and two children could not complete the task due to attention deficit hyperactivity disorder (ADHD).

Twenty-three of the 25 deaf children wore hearing aids bilaterally; one 13-year-old and one 15-year-old did not wear hearing aids. The deaf children were members of specialist integrated hearing impaired units at the seven schools, which used varied pedagogy and communication methods. None of the school records or parent’s consent forms for the deaf children reported any vestibular deficit for the children in this study; however, we were not able to access medical records for the children to rule out this possibility. One school was entirely oral, three schools used a bilingual system of British Sign Language (BSL) and English, often referred to as Sign Assisted English (SAE), and three schools used BSL.

Hearing children were recruited from mainstream classes at these schools and tested in the same environment as the deaf children. The hearing group (N = 64) were 34 females, 30 males, mean age 9.13 years (range 5–15 years).

Deaf and hearing adults had been previously tested on this peripheral vision test and these results were used for comparison with the children’s data. The adult groups were 17 deaf participants, 11 males, six females, mean age 33.25 years (range 18–45) and 18 hearing participants with no loss of hearing and unfamiliar with any signed language, nine males, nine females, mean age 30.28 (range 18–45). The deaf and hearing adults completed the peripheral vision test with exactly the same procedure used for the children’s tests, and both deaf and hearing participants were tested in both the University of Sheffield Psychology department and the Sheffield Grange Crescent Deaf Club. Further detail on the deaf adults’ ages, causes of deafness and BSL use can be found in Table 2. Four out of the 17 deaf participants contracted deafness as a result of in-uterine rubella. It is possible that these participants could have also contracted visual system pathology, and therefore these participants were screened by full ophthalmic examination prior to entry into the study.

### Stimuli and procedure

The visual field test was designed, created, and piloted for reliability, accuracy and repeatability. The design was specifically for young ages of both hearing and deaf children and was transportable. The participating children were asked to detect a flash of light from a briefly illuminated LED, i.e. ‘a star’ presented to the visual periphery, and respond by setting the joystick to one of eight locations so to ‘catch the star’ in a manner similar to playing a computer game. The visual field test was constructed from an acrylic hemisphere 1 metre in diameter and 0.5 m in depth, uniformly painted grey on the concave surface. Ninety-six LEDs (Nichia, 1.5cds) were implanted in the hemisphere beginning 30° peripheral to fixation and then at 5° intervals, for example 35°, 40° and so on to a maximum eccentricity of 85° peripheral to fixation. Twelve LEDs were thus implanted along each of the eight meridians which corresponded to the four cardinal and four intercardinal directions. There were thus eight LEDs at each eccentricity tested. The location of all stimuli could therefore be described according to both the eccentricity from the central fixation target and by the meridian on which it had occurred. All stimuli projected to the participant’s far visual periphery. An adjustable chin and forehead rest

### Table 1 Ages and number of deaf and hearing children tested

<table>
<thead>
<tr>
<th>Age</th>
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<th>Hearing</th>
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</tr>
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</tbody>
</table>

### Table 2 Characteristics of adult deaf participants

<table>
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<tr>
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<th>1st language</th>
<th>Cause of deafness</th>
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<td>BSL</td>
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<td>BSL</td>
<td>In utero rubella</td>
</tr>
<tr>
<td>41</td>
<td>M</td>
<td>Yes</td>
<td>BSL</td>
<td>Unknown</td>
</tr>
<tr>
<td>33</td>
<td>M</td>
<td>Yes</td>
<td>English</td>
<td>Unknown</td>
</tr>
<tr>
<td>35</td>
<td>F</td>
<td>Yes</td>
<td>BSL</td>
<td>Unknown</td>
</tr>
<tr>
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<td>Genetic</td>
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<tr>
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<td>English</td>
<td>Unknown</td>
</tr>
<tr>
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<td>Yes</td>
<td>English</td>
<td>Unknown</td>
</tr>
<tr>
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<td>BSL</td>
<td>Genetic</td>
</tr>
<tr>
<td>38</td>
<td>M</td>
<td>Yes</td>
<td>BSL</td>
<td>Genetic</td>
</tr>
<tr>
<td>22</td>
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<td>BSL</td>
<td>In utero rubella</td>
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<tr>
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<td>Yes</td>
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<td>In utero rubella</td>
</tr>
<tr>
<td>21</td>
<td>F</td>
<td>Yes</td>
<td>BSL</td>
<td>Genetic</td>
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enabled a fixed viewing distance and centralization of the participant’s eye to the fixation monitor and black and white camera placed within it.

Two hundred and twenty-four LED stimuli were each very briefly illuminated (for 200 msecs) in front of the participant’s right eye at three different light intensities. Ninety-six dim stimuli at 83.47cd/m², 96 medium stimuli at 91.81cd/m², and 32 bright stimuli (at eccentricities 40°, 55°, 70°, and 85° only) of intensity 118.94cd/m² were presented in a random order. The test was calibrated by an oscilloscope prior to each testing session to ensure uniformity of time period and degree of illumination after transportation and only the right eye was tested while the left eye was occluded by a plastic shield. The test was carefully explained to each participant in either English or BSL under conditions of full lighting and the directions and instructions for the joystick response were both explained and demonstrated to each participant. The lights were then extinguished in the room and a practice trial began. Participants were seated on an adjustable desk chair, facing the test, chin and head on rests and centrally aligned, and adjusted so that the participant’s eye of testing was centred. All external light sources were eliminated prior to testing and only low level artificial illumination was provided at a constant level of 1.2 cd/m² for all test environments.

Participants first completed a practice trial which consisted of 32 bright stimuli, where four stimuli were presented on every meridian (all at eccentricities of 40°, 55°, 70°, and 85°), and on satisfactory completion of the practice the test was begun. Participants were asked to move the joystick to the position which corresponded with the position in which the light stimulus appeared. For example, if the stimulus occurred on the superior meridian (cardinal direction north), the participant was asked to set the joystick to the upwards setting, and if the stimulus was presented on the inferior nasal meridian (corresponding to south-west), participants were asked to set the joystick to the downwards and left setting. The joystick was only able to move in eight directions, each of which corresponded to the four cardinal and four inter-cardinal directions of the meridians. Thus, if the participant was able to perceive the light stimulus using his or her peripheral vision, then a forced choice response was required, to indicate using the joystick on which of the peripheral vision, then a forced choice response was made. RT was recorded in milliseconds as the time taken to make that correct response. Visual field perimeters widely used in ophthalmology clinics assess the visual field by asking the participant to press a buzzer in response to a light presented in the visual periphery. This new method thus provided an important verification measure of stimulus detection.

The central target was a small glowing yellow LED behind which a camera was hidden. Fixation was monitored throughout testing by the examiner who watched the child’s eye position on a screen monitor viewed under infra-red lighting inside the hemisphere. If fixation was lost for any number of peripheral stimuli, these were repeated at the end of testing.

The right eye only was tested in the children due to time constraints and is in line with the work of other authors (Stevens & Neville, 2006). Visual fields are known to be highly symmetrical in normal subjects (Brenton, 2001). No differences were found between the right and left eye in our adult data.

Results

Percentage correct (PC)

For each participant the total percentage of correct responses across all meridians to all stimulus intensities was calculated for four groupings of eccentricities (30°–40°, 45°–55°, 60°–70°, 75°–85°). These eccentricity groupings were employed because the bright stimuli were only sampled at every third eccentricity due to constraints of time and concentration for the children undertaking the assessment. Figure 1 shows the effect of eccentricity on the mean PC responses made by children aged 5–8 years, 9–12 years and 13–15 years. A three-factor mixed measures ANOVA tested for the effects of group (deaf or hearing), age (5–8, 9–12, 13–15) and eccentricity on performance. As expected the missed stimuli, and hence lowest PC, occurred in the extreme periphery i.e. 75°–85° eccentric to fixation with eccentricity having a significant effect on PC ($F_{(11,89)} = 170.35$, $p < .001$). Age was also significant ($F_{(2,89)} = 170.35$, $p < .001$), with older children showing overall better performance. As can be seen from Figure 1, the effect of group was significant ($F_{(1,89)} = 118.4$, $p < .001$), with overall deaf participants performing worse on average than hearing controls. However, as can be seen from Figure 1, the differences between the groups depended on both eccentricity and age, with the interaction between group, age and eccentricity being significant ($F_{(64,444)} = 9.989$, $p < .001$). The difference between the two groups is most marked in the youngest age group and at eccentricities between 30° and 55°. No other effects were significant, with the effect of stimulus intensity further explored in the next analysis.

In Figure 2, mean PC at each age interval in years for the deaf and hearing groups are separately plotted on the...
ordinate (in percentage) against age (in years) on the abscissa, for each of the three stimulus intensities. Data were not linearly related for either group and were fit separately for deaf and hearing children’s data sets by one phase exponential decay curves as shown in Figure 2. Second-order polynomial curves also fit the deaf and hearing data well, with no significant differences between the r-values, absolute sum of squares, or degrees of freedom in a comparison of the two models of fit. Therefore due to the small number of data points the exact nature of the fit could not be determined with certainty.

For both deaf and hearing groups, PC increased with age, reaching a plateau for each group from age 13 years upwards. In order to test whether the lines of regression differed significantly from one another for deaf and hearing groups, raw data were transformed to linear plots

Figure 1  PC on the ordinate for deaf subjects (circular plots) and hearing subjects (square plots) for four ranges of eccentricities, given on the abscissa for three age brackets (5–8 years, 9–12 years, and 13–15 years) on all three graphs presented. A mean is taken across all stimulus intensities for the age ranges shown and error bars denote the standard error of the mean.

Figure 2  PC on the ordinate for the three intensities of stimuli, the brightest stimuli 2a, the medium stimuli 2b, and the dimmest stimuli 2c, against age in years shown on the abscissa. Deaf results are shown in blue, and hearing in red, with adult results shown by the blue and red dashed lines for deaf and hearing adults, respectively, with exponential regressions applied. Deaf and hearing adult standard errors of the mean (SEM) are shown in black.
by taking the logarithm of age for each of the three stimulus intensities tested. For the brightest stimuli (Figure 2a), linearly transformed data showed no significant difference between regression coefficients (\( p = .49 \)), and no significant difference for y intercept regressions (\( p = .38 \)). For the medium intensity stimuli (Figure 2b), no significant difference was found between regression coefficients for the two groups (\( p = .45 \)), and no significant difference for the regression y intercepts (\( p = .997 \)). For the dimmest target stimuli (Figure 2c), however, there was a significant difference (\( F(1,72) = 8.17, p = .005 \)), and y intercept values were considered significantly different between the two groups (\( F(1,72) = 24.94, p < .001 \)). For the bright stimuli (2a), the deaf and hearing groups converged at 11.7 years, for the medium stimuli (2b), groups converged at 13.8 years of age, and for dim stimuli, intersection occurred at 14.6 years of age.

There was no difference in PC between deaf and hearing adults (\( p = .94 \)), and these adult data are presented in Figure 2 for comparison with children’s data and for determining adult levels of vision in deaf and hearing children, respectively, where adults’ results are shown by the dashed lines on each of the three graphs. For all three stimuli (2a, 2b and 2c), both deaf and hearing reached adult performance at 11 years of age. \( T \)-tests were conducted between deaf and hearing children and adult data, for children in the following age groupings due to the small numbers aged (5–7), (8–10), (11–12) and (13–15) and corrected for multiple comparisons by Bonferroni adjustment, and were found not to differ significantly from adult data at age 11–12 and 13–15 years.

**Reaction time (RT)**

For each participant, mean RTs to correct responses only were calculated across the four groupings of eccentricities (as for PC) and pooled across all meridians and stimulus intensities. Figure 3 shows the effect of eccentricity on the RTs made by children aged 5–8 years, 9–12 years and 13–15 years old. A three-factor mixed measures ANOVA tested for the effects of group (deaf or hearing), age (5–8, 9–12, 13–15) and eccentricity. As can be seen from Figure 3, RT was significantly slower at the more peripheral eccentricities (\( F(11,89) = 26.67, p < .001 \)). The effect of age was significant (\( F(2,87) = 29.54, p < .001 \)), with RT tending to decrease with age. Overall the deaf participants had significantly slower RT (\( F(1,89) = 118.4, p < .001 \)) than the hearing controls. However, as can be seen from Figure 3, the effect of group on RT depends on both age and eccentricity. The interaction between group, age and eccentricity was significant (\( F(64,434) = 9.989, p < .001 \)). In the 5–8 age group the deaf children appear to have slower RT than hearing children; there is little difference in the 9–12 age group, with the 13–15 age group showing more complex differences that depend on eccentricity, with deaf adolescents showing quicker RT beyond 60° eccentricity. No other effects were significant, with the effect of stimulus intensity on RT further explored for the deaf and hearing children in the following analysis.
Mean RTs were calculated for each age interval in years for the deaf and hearing groups separately and were plotted on the ordinate (in msec) with age (in years) on the abscissa for each of the three stimulus intensities in Figure 4. Age and RT were not linearly related for either group and were fit for each data set by one phase exponential decay curves consistent with Kail (1991) and Cerella and Hale (1994). Again, it was difficult to determine the exact fit for the data, given the small number of data points, and no significant differences were found between one phase exponential and a second-order polynomial curve fits. Both the deaf and hearing groups showed RT reduction with age to all stimuli, consistent with Goodenough (1935), Rose, Feldman, Jankowski and Caro (2002) and Der and Deary (2006). The younger deaf children, aged approximately 5–10 years old, demonstrated slower RTs than age-matched controls; and this difference decreased non-linearly as a function of age between the groups. Concerning the adult data, RT was significantly faster in the deaf adults than hearing controls ($F_{(1,58)} = 4.11, p = .03$) and this can be seen in Figure 4 where mean adult results are shown by the dashed lines on each of the three graphs.

To test whether the lines of regression differed significantly from one another for deaf and hearing groups, the logarithm of age was calculated from the raw data and linear transform regressions applied to the two groups. The regression coefficients (b) were calculated separately for the deaf and hearing groups and to each of the three stimulus intensities. For linear transforms of the data from the brightest stimuli there was no significant difference between the two regression coefficients ($p = .60$), and there was no significant difference between the y intercept values ($p = .57$). For the medium stimuli (Figure 4b), there was a significant difference between regression coefficients ($F_{(1,72)} = 22.60, p < .001$), and y intercept values for both groups were significantly different ($F_{(1,72)} = 68.58, p < .001$). For the dimmest stimuli (Figure 4c), there was a significant difference between the regression coefficients ($F_{(1,72)} = 68.35, p < .001$), and these y intercept values were again significantly different ($F_{(1,72)} = 193.7, p < .001$). The strongest effects of hearing status were seen when the children were asked to respond to the dimmest stimuli (Figure 4c). The deaf and hearing exponential decays intersected at age 10.8 for the bright stimuli (4a), age 12.4 for the medium stimuli (4b) and age 11.7 for the dim stimuli. T-tests were conducted between deaf and hearing children and adult data in the following age groupings due to the small numbers: 5–7, 8–10, 11–12 and 13–15, and were corrected for multiple comparisons. Children’s RTs were significantly slower at ages 5–7 and 8–10 years, but were found not to differ significantly from adult data at age 11–12 years. T-tests between deaf and hearing 13–15-year-olds were significantly faster than hearing controls ($p = .01$).

**Discussion**

Both deaf and hearing children showed improvement in the accuracy of detecting and reporting stimuli in their far peripheral visual fields throughout childhood. Where PC results are considered, with the exception of younger deaf children with dim stimuli, deaf children showed similar developmental trajectories to hearing children in reporting stimuli accurately in the far visual periphery (Figure 2). This continued period of improvement to children’s performance could represent a difference in visual attention which moves from a central reference towards the periphery during development. An alternative theory is that peripheral vision may continue to mature throughout childhood with a developmental
improvement of the retinal and post-receptoral response to peripheral visual stimuli. However, further investigation is needed to address the mechanism of this developmental visual field increase in all children.

Deaf and hearing participants differed significantly in RT to the medium and dim stimulus intensities tested. However, the significant difference reversed in direction between the younger deaf children (aged 5–10 years) who showed slower RTs than age-matched hearing controls; and the older deaf children (aged 13–15 years) who demonstrated faster RTs than controls. The significantly slower RT by deaf children (aged 5–10 years) was shown by significantly higher y intercepts in Figure 4b and 4c. Younger deaf children between the ages of 5 and 10 years therefore appeared disadvantaged on these peripheral vision measures compared to their hearing peers and this finding is consistent with Netelenbos and Savelbergh (2003), Rettenbach et al. (1999), Quittner et al. (1994), Smith et al. (1998), and Myklebust (1964).

Detection of the dimmer and most eccentric stimuli may require a higher degree of visual attention than the brighter, less eccentric stimuli and young deaf children have shown attentional delay in comparison with their hearing peers (Quittner et al., 1994; Smith et al., 1998). Therefore it may be that an extended development period for visual attention is needed before deaf children perform equally to or better than the age-matched hearing children. Dye, Hauser and Bavelier (2008) have suggested that a key attribute of deaf individuals’ vision is a redistribution of attentional resources to enhance attention to peripheral visual space. This suggestion finds support in the results from the deaf adolescents and adults in our study who reacted more quickly to low level stimuli in the far periphery. The accompaniment of these attentional changes by neural modifications and cross-modal reorganizations in cortical multisensory and auditory regions also suggested by Dye et al. (2008) may represent an underlying potential for visual compensation, which develops later when attention or visual maturity allow.

It is interesting that the age at which the deaf and hearing developmental trajectories were seen to intersect was in the age range of approximately 11–12 years, with a seeming peripheral vision advantage identified in deaf adolescents aged 13–15 years. The age of 11–12 years at which the deaf participants moved from a position of visual disadvantage to visual enhancement thus appears a crucial point in the deaf child’s visual development and coincides with the report by Dye et al. (2009), which highlighted a behavioural advantage on their selective visual attention task in deaf 11-year-olds. Although our study did not identify an advantage in the deaf by pre-adolescence as did Dye et al., it is worth noting that the numbers of children in our study were much smaller. However, the eccentricity of peripheral vision tested began at 30° to fixation (10° further peripheral than previously tested) and the later age of visual compensation we have suggested may indicate a possible trend to visual enhancement beginning in the near periphery and moving further into peripheral vision with age.

The wider literature has reported decreased cognitive and conceptual ability generally in young deaf children (Marschark, Rhoten & Fabich 2007, Kyle & Harris, 2006; Traxler, 2000). Consistent with these reports, the younger deaf children demonstrated reduced ability to locate and report the dim peripheral light stimuli between the ages of 5 and 10 years, shown by the significantly lower y intercept for deaf children to PC (Figure 2c). However, it is important to note that the deaf children’s development regressions were not significantly different from hearing children’s for the brightest stimuli for RT and PC (Figures 2a and 4a), and for the medium stimuli for PC (Figure 4b), and the different stimulus intensities were presented mixed in a random order. Therefore it can be assumed that the deaf children sufficiently comprehended the task, performing similarly to controls for the brightest stimuli for RT and brightest and medium stimuli for PC. While the conceptual difficulty reported in perimetry assessment by Whiteside (1976) may be exacerbated in young deaf individuals based on poorer cognitive performance, it seems unlikely that differences in conceptual or cognitive abilities between deaf and hearing children provoked the difference in peripheral visual performance when both groups performed equally well to the brighter intensity stimuli. The difference in PC only to the dimmest stimuli tested may in part explain earlier reports which have found peripheral vision maturity to be as young as 5 years old using intensities which were very similar to the brightest stimuli in our study (Cummings et al., 1988). This indicates that results with regard to peripheral vision maturity may be dependent upon the light intensity of the presented stimuli.

As previously mentioned, deaf adults demonstrated reduced RTs to all stimuli on this peripheral vision task, and therefore deaf children were compared with deaf adults and hearing children with hearing adults when estimating maturity of response to adult-like level in this test. RT and PC did not reach levels which compared with deaf or hearing adult data until at least 11 years for RT and PC for both deaf and hearing children. The visual field indeed appeared constricted in terms of PC responses for both deaf and hearing children aged 5–8 years (see Figure 1), as stimuli that were most frequently incorrectly responded to or missed occurred in the extreme periphery for all children tested. This low detection rate of stimuli in the furthest periphery in young hearing and deaf children is consistent with a wide range of reports on children’s peripheral vision (Bowering et al., 1997; Lakowski & Aspinall, 1969; Liao, 1973; Aspinall, 1976; Wilson et al., 1991; Morales & Brown, 2001; Wabbels & Wilscher, 2005).

The greatest difference in peripheral vision development between deaf and hearing children occurred in RT. Deaf adolescents were significantly faster than hearing
controls by the age of 13 years, which is consistent with previously reported adult peripheral RT performances and with the peripheral attention advantage in deaf adolescents and adults reported by Dye et al. (2009). The linearly transformed raw data, fit by regression lines independently for deaf and hearing children, revealed a significant difference between the deaf and hearing regression coefficients for medium and dim stimuli. The RT rapidity observed in deaf adults was late to arise in deaf children, and intersection of the lines for the deaf and hearing children occurred at 10.8 years for the bright stimuli, 12.4 years for the medium stimuli, and 11.7 years for the dim stimuli. Interestingly, the age at which deaf children demonstrated RTs that were within normal limits of deaf or hearing adult responses was similar to the ages of intersections of deaf and hearing regressions. This was at 12 years for the bright and medium stimuli, and 13 years for the dim stimuli and therefore overlapped with the age at which deaf children started to perform better than hearing. Whether this is indicative of a certain level of maturation needed in peripheral vision before the compensation observed in deaf adults in this study and by several previous authors (Loke & Song, 1991; Bosworth & Dobkins, 2002; Neville & Lawson, 1987; Stivalet et al., 1998; Proksch & Bavelier, 2002; Parasnis & Samar, 1985, Stevens & Neville, 2006; Buckley et al., 2010) requires more investigation.

The difference between deaf and hearing children's PC and RT results to the dimmest stimuli (Figures 2c and 4c) is interesting in regard to Bowering et al.'s (1997) report of constriction of the visual field aged 5 years and above only to lower stimulus intensities in hearing children. As previously mentioned, both hearing and deaf children demonstrated constriction of the visual field in childhood (see Figure 1), yet the constriction of the visual field to the lower intensities was more notable in the deaf children in our study. This may represent a slowly developing redistribution of visual attention to the periphery, or a developing maturation of peripheral retina and post-receptoral visual pathway structure. The rate of post-receptoral maturation and spatial frequency tuning of the specific retinal, geniculate, and cortical cell receptive fields is so far unspecified, but is thought to continue throughout development. These ongoing maturations have often been a suggested explanation for the continuing improvement observed in peripheral visual function beyond that of central vision (Brown, Dobson & Maier, 1987; Mohn & Van Hof-van Duin, 1986; Wilson et al., 1991). It is possible that maturations of these pathways are, in hearing children, contributed to by auditory stimuli. Stein and Stanford (2008) document the contributions made by the synergy of senses to the magnitude of sensory response. Therefore a hypothesis of continuing high grade development, calibrated by integration with the auditory system, is a possible explanation for the initial peripheral vision disadvantage which diminishes to the extent of visual compensation, as observed by this study. An electrodiagnostic study which measures sensory response at peripheral retinal locations might provide further information to distinguish whether the disadvantage observed in young deaf children in peripheral vision is attentional or sensory in nature.

Deaf adults have shown differences in right and left visual fields, but not between right and left eyes. Clarke, Bellmann, Meulli, Gil and Steck (2000) and Neville and Lawson (1987) reported a right hemisphere advantage for motion processing in the left visual field. Fine et al. (2005) reported a predisposition for the right auditory cortex more than the left auditory cortex, to be recruited by cross-modal auditory-visual cortical plasticity in deaf individuals and employed in motion and spatial processing which affects the visual field. These findings have interesting implications for children with cochlear implants, and in regard to unilateral or bilateral cochlear implantation. Given the increasing evidence for neural reorganizations in deaf individuals, there is a necessity to repeat the above measures with cochlear implanted congenitally and profoundly deaf children. Cochlear implantation may affect vision such that peripheral vision detection can mature in a manner more similar to the hearing children in this study, or such that visual compensations secondary to cortical plasticity no longer occur.

Deaf children demonstrated greater variability than hearing children, evidenced by lower standard error values in the hearing children's age group means (see Figures 2 and 4) which remained even when the different numbers of participants were accounted for. The deaf children represented a range of communication methods, and Connor, Hiebr and Arts (2006) have reported that teaching strategy may be related to deaf children's speech and education performance. During data collection a high degree of variability in language abilities of deaf children within the various schools was noted. The group of deaf children included those with limited or no English skill. However, the majority of deaf children tested had learnt English as their first language, and language development in deaf late learners of a signed language tends to be delayed when compared with that of the early signer (Mayberry & Lock, 2003). The auditory-verbal language network including Broca’s area and the inferior parietal cortex have been shown to become modified as a consequence of acquiring orthographic language skills (Petersson, Reis, Askelof, Castro-Caldas & Ingvar, 2000), and therefore a larger study which can incorporate language skill and BSL proficiency is needed to assess these effects on vision.

It has been reported that vestibular and proprioceptive information integrate in the early stages of visual information processing (Sauvan & Peterhans, 1995); and Hatzitaki, Zisi, Kollias and Kloumourtzoglou (2002) reported a strong correlation between hearing adolescents’ static vestibular control and their ability to perceive and process visual information. Therefore, while the children in this study were not known to have been
We are grateful to the Royal National Institute for the Visual Performance previously reported in deaf adults been found which may reconcile the different reports of advantage was consistent with older deaf adolescents which is late in terms of visual development, and this is consistent with published reports of a large number of visual complications associated with deafness (Suchman, 1967; Fillman, 1987; Regenbogen & Godel, 1985). However, our study presents data for the first time on the developmental trajectories of deaf and hearing children with regard to peripheral vision in the far peripheral visual field and for a range of stimulus intensities.

**Conclusion**

Deaf children’s developmental performance on this specifically paediatric designed perimetry method differed subtly from hearing children’s. Younger deaf children (aged 5–10 years) showed slower RTs to and less ability to detect and accurately report far peripheral dim stimuli. However, these differences diminished throughout childhood, with similar RTs and accuracies in deaf and hearing 11–12-year-olds. Thus the synergy of auditory and visual stimuli would initially appear beneficial to peripheral vision development in young children. Visual compensation for deafness was first evident in the RTs of deaf adolescents aged 13 years old, which is late in terms of visual development, and this advantage was consistent with older deaf adolescents and adults. Thus, though a small study only, results have been found which may reconcile the different reports of visual performance previously reported in deaf adults and deaf children.

**Acknowledgements**

We are grateful to the Royal National Institute for the Deaf (RNID) who funded Charlotte Codina’s PhD, Dr Alison Scope for kind assistance in collecting children’s data, Richard France and Richard Stacey for help in recruiting deaf participants, Richard Squires and staff of Allerton Grange School in Leeds, Lower Meadows Primary School, Greystone’s Primary School, Mrs Bentley and staff at Wombwell Park Street Primary School, Miss Winn and staff at Bramley Grange Primary School, Castleford High School, and The Rookeries Junior and Infant School, Pontefract. We would also like to thank the Editor, Professor Scania de Schonen, for helpful suggestions during the review process.

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Received: 24 February 2009

Accepted: 2 September 2010

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