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Action video game players and deaf observers have larger Goldmann visual fields

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ABSTRACT

We used Goldmann kinetic perimetry to compare how training and congenital auditory deprivation may affect the size of the visual field. We measured the ability of action video game players and deaf observers to detect small moving lights at various locations in the central (around 30° from fixation) and peripheral (around 60°) visual fields. Experiment 1 found that 10 habitual video game players showed significantly larger central and peripheral field areas than 10 controls. In Experiment 2 we found that 13 congenitally deaf observers had significantly larger visual fields than 13 hearing controls for both the peripheral and central fields. Here the greatest differences were found in the lower parts of the fields. Comparison of the two groups showed that whereas VGP players have a more uniform increase in field size in both central and peripheral fields deaf observers show non-uniform increases with greatest increases in lower parts of the visual field.

1. Introduction

Performance in visual peripheral tasks can be enhanced with training (Ball, Owsley, Sloane, & Roenker, 1993). In some cases the effect of training is very specific, for example to specific location in the visual field, in others it is more general (see Ahissar & Hochstein, 2000, for a review). It has also been shown that past experience can affect performance in such visual tasks. A lifetime of sensory deprivation of one modality, for example due to deafness, can lead to enhanced performance in another, for example vision (Bavelier et al., 2000; Bavelier, Dye, & Hauser, 2006). Also habitual or recent exposure to a visual task, for example video game playing, can also improve visual performance (Green & Bavelier, 2003, 2006, 2007). In this paper we further explore the nature of this improvement in habitual video game players, Experiment 1; and deaf observers, Experiment 2.

Green and Bavelier (2003) showed that habitual video game players (VGP) have better visual performance than non-video game players (NVGP) on a range of different tasks presented within 30° of fixation. However, the video game players reported playing games in a field of view that typically extends no more than 18° eccentric of fixation. So video game playing appears to be influencing performance beyond that stimulated by these games. Green and Bavelier (2003) were careful to select players of action games where virtual 'enemies' or obstacles can appear at any location in the visual field. They argued that their findings demonstrate 'enhanced allocation of spatial attention over the visual field, even at untrained locations, in video game players' (p. 535). An obvious problem with interpreting these results is determining whether video game playing increases visual ability across the visual field or whether video game playing attracts those who already have better abilities. This problem was addressed in the final experiment of Green and Bavelier (2003) where they found that a group of NVGP could show enhanced performance after a short regime of action game playing.

It has also been reported that deaf observers in peripheral visual tasks such as detecting subtle motion changes, show greater sensitivity to stimuli presented away from the fixation point than hearing controls (Bavelier et al., 2000; Bosworth & Dobkins, 2002; Bavelier & Neville, 2002, for a review see Bavelier, Dye & Hauser, 2006). Bosworth and Dobkins (2002) used a detection of motion task with stimuli presented at different locations across the visual field, and found that deaf observers performed better in the periphery than hearing controls but that the hearing observers performed better in central vision than the deaf observers. Bavelier et al. (2000), found enhanced visual performance in congenitally deaf individuals whilst monitoring peripherally moving stimuli. Neville and Lawson (1987a,1987b) found a deaf advantage in detecting stimuli in peripheral vision. Stivalet, Moreno. Richard, Barraud, and Raphael (1998) found that deaf observers were faster than hearing people at locating a target amongst distractors in peripheral vision. Proksch and Bavelier (2002), in agreement with Parasnis and Samar (1985), suggested that deaf observers possess greater attentional resources in the periphery when compared to hearing controls.

The majority of previous studies have tested deaf observers' vision within about a central 16° radius of fixation, typically asking observers to fixate the centre of a closely viewed computer

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monitor and then presenting test stimuli near the display edges (but see Rothpletz, Ashmead, & Thorpe, 2003). The normal visual field extends to as much as 100° around fixation and so the area explored in most previous studies of both video game players and deaf observers is relatively small. Therefore in both our experiments we used Goldmann kinetic perimetry, which can present stimuli at these extents, to test how far enhanced performance extends into the periphery. Stevens and Neville (2006) using the Humphrey analyser, another standard kinetic perimetry test, have found that deaf observers were better at detecting motion over a larger area of the visual field than control observers. They tested one eye of each participant out to about 60° we always tested both eyes separately (see later).

Goldmann kinetic perimetry is a standard clinical test of visual field sensitivity used in UK hospital ophthalmology departments. While gaze remains directed to a central fixation point the observer's task is to press a button when they detect a spot of light, projected onto the inside of a white illuminated half-dome, that has moved along a radius from the outer periphery towards the fixation point. Within 30° of fixation is clinically referred to as the *central visual field*, with the rest referred to as the *peripheral visual field*. We shall use these definitions throughout this paper. These different fields are assessed using targets of different sizes and at various locations in the visual field (see Section 2.2.1). These clinical definitions of central and peripheral may sometimes be at odds with the use of these terms in the visual psychophysics and visual attention literature, for example, so care needs to be taken if the reader is comparing findings from different sources.

The central visual field, as defined above, is at the edge of the eccentricities tested for video game players by Green and Bavelier (2003) and the peripheral visual field is well away from the parts of the retina that would typically be stimulated by a video game, or indeed that tested in most of the studies of deaf vision described above. We might therefore expect both larger central and peripheral visual fields in VGP compared to NVGP if players show enhanced spatial attention across the entire visual field. Alternatively if stimulation by the game is important we might expect larger central fields in VGP but peripheral fields of similar size in both groups. In some of Green and Bavelier's tests the stimuli were presented at a small range of 'round the clock' locations, however they do not report whether video game playing enhanced visual performance in any particular parts of the visual field, so this was tested in Experiment 1. For the deaf observers, in Experiment 2, we similarly used Goldmann perimetry to test visual performance in areas of the visual field little explored previously. Given the findings of Stevens and Neville (2006) we would expect deaf observers to have larger visual fields than hearing controls, these authors also found that the deaf observers showed similar differences in all sectors of the visual field. Stevens and Neville (2006) only tested the fields of the right eye and so could not test for any differences reported previously between left or right visual fields that are possibly dependent on sign language use (Bosworth & Dobkins, 2002; Neville & Lawson, 1987b). Therefore in both our experiments we measured both eyes separately.

Within each experiment data was compared between the experimental and age and gender matched control groups. We also compared the data from the VGP and deaf participants and separately the data from the two control groups.

2. Experiment 1 – video game players

2.1. Method

2.1.1. Participants

Ten action video game players (VGP, 5 males and 5 females, mean age 22 years) and ten non-video game players (NVGP, 5 males and 5 females, mean age 20.2 years) took part in Experiment 1. All participants were right-handed. It was important that the two groups were closely matched for age since fields are known to decrease in size with age (Haas, Flammer, & Schneider, 1986). None of the participants in Experiment 1 were deaf or users of sign language. Green and Bavelier's criteria for VGP participants was that they played at least 4 days per week for at least 1 h per day in the 6 months prior to taking part in their study (Green & Bavelier, 2003). Most of our VGP group would describe themselves as habitual/regular players. The mean number of hours played per week was 5.2 h (range 1–14 h). The VGP group had been playing games for a mean of 10 years (range 5–19 years). The NVGP either never, or rarely, played games and none had played in the 6 months prior to the experiment. The first Person video games played by the VGP group were similar to those reported by Green and Bavelier (2003) and included: *Grand Turismo, Tomb Raider, Harry Potter, Mario Carts, Grand Theft Auto, Halo, Golden Eye, Metroid Prime and Sonic.*

All observers had good stereo acuity of at least 60″ of arc as assessed using the Frisby stereotest. None showed any evidence of suppression of binocular single vision assessed using Worth's Lights test of simultaneous perception at a 6 m viewing distance. Their visual acuity was at least 6/9 in either eye with contact lens correction if required (measured monocularly with a back illuminated Snellen chart at 6 m and a reduced Snellen chart at 1/3 m). No participant wore spectacles in the experiment as the frames would obscure parts of the peripheral field. No participant exhibited any vergence anomalies - assessed at near (1/3 m) and distance (6 m), with prism cover test and prism fusion range (see Ansons & Davis, 2001; von Noorden, 2002). There were no significant differences between the two groups on any of these measures (highest $t = 1.387$ n.s.).

2.2. Procedure

This and Experiment 2, followed declaration of Helsinki guidelines and were approved by the University of Sheffield ethics committee. The participant was given written instructions about the purpose of the study and signed a consent form. Then various orthoptic measures were assessed (see above). Their visual fields were then measured.

2.2.1. Goldmann perimetry

The visual fields were measured using the same machine by either the second or third author. Both examiners had received the same training in the use of the Goldmann perimeter, and implemented the measurement procedures in the same way. Importantly both examiners collected data from equal numbers of the VGP and NVGP group (see below for tests of differences between these testers).

The perimeter of the visual field was recorded monocularly for each participant using Goldmann perimetry. The Goldmann instrument was calibrated at the start of each session. The background within the test was uniformly illuminated to about 10 candelas$^{-m^2}$. A circular light target (4*Ie* – with area 0.25 mm^2, luminance 328 candelas$^{-m^2}$) was used to map the peripheral (larger) visual field. A fainter light target (2*Ie* – with area 0.25 mm^2 luminance about 20 candelas$^{-m^2}$) was used to map the central field. The testing was conducted in a light proof room with extinguished room lights. The observer's head was kept steady on a chin-rest and the non-assessed eye was occluded. The observer was asked to fixate a central light target at the pole of the inside of the half-dome. Behind the fixation point was attached an eyepiece through which the examiner ascertained correct fixation before and during each stimulus presentation. If fixation was lost, the test stimulus was immediately reset and repositioned at the far periphery of another random test meridian. Prior to any data recording the stimulus and task were demonstrated to the participant with the brighter target. All these aspects of assessing the field are standard clinical procedure.

The order of testing the right or left eye was allocated randomly. The field of vision for either eye was tested across the 360° hemisphere in steps of 30° in a different random sequence of positions for each participant and for each eye and each field. The peripheral field was plotted first (about 60° radius from fixation), and then the central field (extending to about 30° radius from fixation).

The target was moved manually from a position 100° eccentric to the fixation point along a radius (longitude) at a speed of about 3–5° s^{-1} until the participant pressed a button to indicate the target had been detected (Johnson & Keltner, 1987). The examiner then recorded this location on the standard Goldmann chart. Presentations were repeated if the examiner noticed a deviant movement of the eye away from the fixation point or if any point appeared anomalous. Once complete the target was briefly introduced at various locations within the plotted visual field area, i.e. where the observer should always detect the light, to check both the accuracy of the observer's previous responses and to check for any scotoma. No participant showed evidence of scotoma.

Once the field data had been collected the observer was given a questionnaire that asked about their recent video game exposure and, if any, which games they played, for how many hours each week and at what age they began playing. Both testers did not know whether the observer was a computer game player until all testing was complete. In order to balance the age and genders of the two groups we selected participants from a pool of already collected fields (by the second author) such that the two groups were matched for gender and age. We gave the members of this subsample the same questionnaire as above, again after the fields had been collected. When the different tester was added as a factor in the analyses described below no significant differences were found between the two testers or any interactions with this factor and so the data from each tester were amalgamated.

2.3. Results

Fig. 1 shows the mean central (red) and peripheral (blue) fields of the video game players, filled symbols and bold lines, and non-video game players, open symbols and dashed lines, for the left eye, Fig. 1a, and the right eye, Fig. 1b. From this figure it would appear that the size of both central and peripheral fields are larger in both eyes for the VGP. To test this the area of each quadrant (Q1–Q4) of each eye and each field was calculated for every participant by summing the area of each of the three triangles formed between a pair of points and the fixation point. Three of these triangles are shown for the central field in Fig. 1b. Quadrant areas were used as these best captured the performance of each participant and importantly it allows the findings of this experiment to be compared with those of Experiment 2. However quadrant area data was found to be non-normally distributed, as might be expected given that the area is related to the square of our measured locations, and therefore any difference between groups in such locations would be squared. Statistical analyses were therefore performed on the square root of the area of each quadrant.[1]

The central and peripheral square root of quadrant area data were analysed in two separate three factor mixed measures analyses of variances (ANOVAs). One factor was Person (VGP or NVGP), another factor was eye (left or right) and the other factor was quadrant (see Fig. 1). Note that quadrant refers to the left eye, and the matching quadrants in the right eye: for an observer with normal visual fields a particular field of the left eye (central or peripheral) should be a vertical mirror image of the corresponding field in the right eye (Brenton, Phelps, Rojas, & Woolson, 1986). For example, as can be seen in Fig. 1, the shape of the field in Quadrant 1 (Q1) of the central field in the left eye is the vertical mirror image of Quadrant 2 (Q2) in the right eye, and so on for the other quadrants.

For the central field on average the VGP group detected the target at more eccentric locations which led to larger field areas (2926 deg^2) than the NVGP group (1970 deg^2), $F_{1,18} = 5.227$, $p < 0.05$. Consistent with Brenton et al., (1986) there was no significant difference between the two eyes, $F_{1,18} = 0.0004$, n.s., (not significant), or interaction of the Person (VGP/NVGP) and eye factor, $F_{1,18} = 0.452$, n.s., so the slight difference apparent in Fig. 1 was not significant. The quadrant factor was significant, as expected given the normal shape of the visual fields in Fig. 1, $F_{3,54} = 6.830$, $p < 0.001$. None of the interactions that included the group factor were significant for the central field data, largest F value, $F_{3,54} = 2.082$, n.s.

For the peripheral field data a similar pattern of results was found to that in the central field. For the Person factor, again on average the VGP group detected the target at more eccentric locations (area 8744 deg^2) than the NVGP group (area 7637 deg^2), $F_{1,18} = 8.588$, $p < 0.01$, and there was no significant difference between the two eyes, $F_{1,18} = 0.321$ n.s. As expected the quadrant factor was significant, $F_{3,54} = 31.397$, $p < 0.0001$, but again all interactions involving the group factor were not significant for the peripheral field data, largest F value, $F_{3,54} = 1.416$.

Fig. 2 shows the mean area for each quadrant averaged across each eye, as no significant differences were found between the eyes. Fig. 2a shows the data for the Central Field and 2b for the Peripheral Field. Note that the quadrant numbers (Q1–Q4) refer to those for the left eye and the mean values include the matching quadrants in the right eye (Q2, Q1, Q4 and Q3, respectively).

2.4. Discussion of VGP data

Figs. 1 and 2 show that habitual video game players (VGP) appear to have larger central and peripheral visual fields than non-video game players (NVGP), around 1000 deg^2 larger for each field. The improved performance appears uniform across the entire field (at least in the central field) and is similar in both eyes. However if these differences seen in Figs. 1 and 2 were expressed in percentage terms then improved performance is more marked in the central fields.

The finding of increased central visual fields is consistent with the findings of Green and Bavelier (2003). The fact that this increased sensitivity is also present in the peripheral field suggests that video game stimulation of that part of the visual field is not necessary to produce the effect. As described earlier Green and Bavelier (2003) did not report whether video game playing enhanced visual performance in any particular parts of the visual field. Our findings are that the enhancement does not depend on location in the central field. It suggests that it is the video game playing that is affecting performance. We attempted to correlate number of years and/or hours per week playing games with field sizes but the results (not reported here) were unclear, a larger sample size would be needed to test this more thoroughly, as many factors may probably be involved. However, Green and Bavelier (2007) found that enhanced performance in visual tasks could be observed in NVGP even after short (1 h per day for 10 days) periods of training on action video game. It would therefore be interesting to track such performance changes across the entire visual field with progressive game exposure in NVGPs.

[1] Note that ANOVAs conducted on the raw measurements rather than area showed exactly the same patterns as described for the area analysis reported here. Reporting area made it far easier to interpret any differences between groups in both experiments.

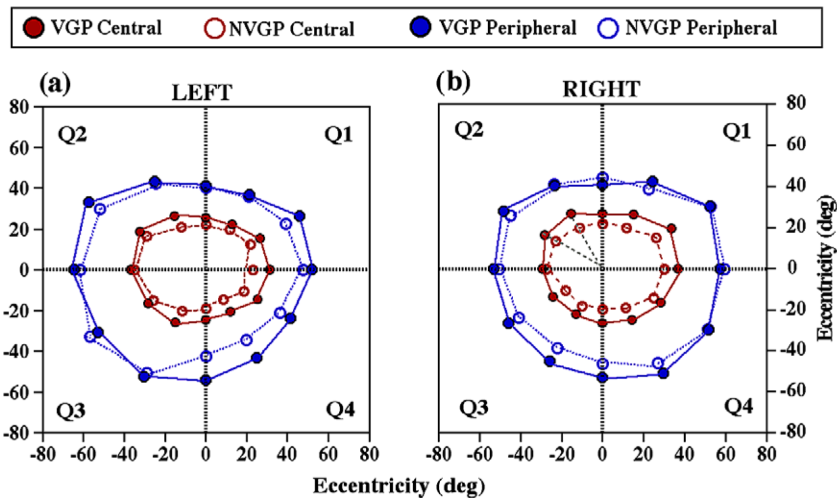

Fig. 1. The mean visual fields of the 10 video game players (VGP) and 10 non-video game players (NVGP). Fig. 1a and b, mean central (red – around 30° from fixation) and peripheral (blue – around 60° from fixation) fields of the VGP (filled symbols) and NVGP (open symbols) groups for the left, Fig. 1a, and right, Fig. 1b, eyes. Each point indicates the mean location at which a moving spot of light was detected. To aid clarity error bars are not shown on this figure but the standard errors for both groups, for both eyes and for both groups were on average about 3°. The centre of each graph indicates the fixation point. The grey dashed lines in Fig. 1b, indicate the boundaries of the three triangles that would be used to calculate the area of Quadrant 2 (Q2), in this example for the central field for the NVGP group. The mean central field of the VGP observers was 955 deg^2 bigger, and the peripheral field was 1107 deg^2 bigger than those of the NVGPs, see Fig. 2. Both fields appear to be uniformly larger for the VGPs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

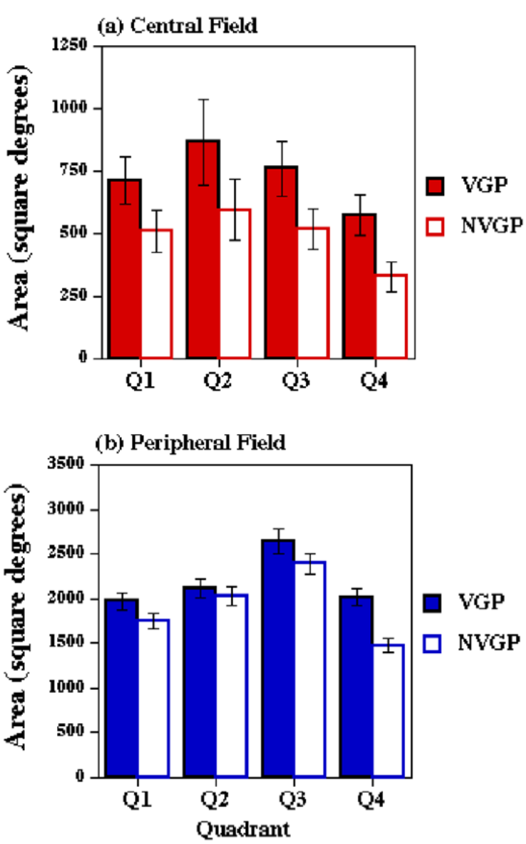

Fig. 2. Column graph of the mean areas of each quadrant of the visual fields averaged across the left and right eyes of 10 VGP (filled columns) and 10 NVGP (open columns). Note that the quadrant numbers (Q1–Q4) refer to those for the left eye and the mean values include the matching quadrants in the right eye (Q2, Q1, Q4 and Q3, respectively). Fig. 2a shows the mean central field areas and Fig. 2b the mean peripheral field areas. The error bars show ± one standard error of the mean. Note the different range of the abscissa scales in Fig. 2a and b.

3. Experiment 2 deaf observers

3.1. Participants

Thirteen congenitally deaf took part in this experiment, 8 males and 5 females, mean age 29.7 years (range 19–39 years), all had severe binaural hearing loss such that hearing aid amplification must be supplemented by lip reading. From Table 1, which shows deaf participant details, it can be seen that our random sample was a heterogeneous group. Causes of deafness were varied and included hereditary deafness, pre-mature birth and, as is typical, most often the cause was not known. No deaf participant had a systemic disorder known to affect the eye. The deaf group included a range of individuals, from those who did not use British Sign Language (BSL) in conversation to those who considered BSL their first language. The hearing control group consisted of 8 males 5 females, mean age 26.4 years (range 21–38 years), all with good binaural hearing and no experience with BSL. There was no significant difference between the ages of the two groups. All participants were emmetropic and had unaided Snellen's visual acuity of 6/6 in either eye with mean visual acuity not significantly different between groups, there were no significant differences between the two groups in any of these vision tests. There was one left-handed participant in the deaf group with all other participants being right-handed.

3.2. Procedure

Written consent was obtained and a similar set of orthoptic tests as those in Experiment 1 were performed on the participants. The Goldmann visual fields were then measured by the second author in the same way as in Experiment 1 except that the field of vision for either eye was tested across the 360° hemisphere in steps of 15° instead of the 30° in Experiment 1, see Fig. 2. This was to explore in more detail the nature of any field differences. The deaf participants were tapped on the shoulder to indicate the start and end of the test and there was sufficient light from the background illumination of the test for them to be given further instructions by the second author via lip reading and/or BSL.

Table 1
Deaf participant details.

Participant	Gender	Age (years)	Cause of deafness	Main language	Years signing	Videogame player
1	F	22	Genetic	BSL	22	No
2	M	23	Prematurity	English	0	Yes
3	F	19	Unknown	English	0	No
4	M	33	Unknown	BSL	14	No
5	M	33	Genetic	BSL	8	Yes
6	M	25	Unknown	English	0	No
7	M	32	Unknown	English	31	Yes
8	M	35	Unknown	English	8	Yes
9	F	38	Unknown	BSL	38	No
10	F	39	Unknown	BSL	36	No
11	M	31	Unknown	English	15	Yes
12	M	29	Genetic	BSL	7	Yes
13	F	27	Genetic	BSL	19	No

3.3. Results of deaf observers

Fig. 3a and b, left and right eye, show the mean central (red) and peripheral (blue) fields of the deaf (filled symbols) and hearing groups (open symbols). As in Experiment 1 two separate three factor mixed measures analysis of variances were conducted on the square root of the area of each quadrant of an observer's field. These showed that deaf observers had significantly larger central visual fields (areas 3206 deg^2 v 1713 deg^2), $F_{1,24} = 14.434$, $p < 0.001$, and significantly larger peripheral visual fields (areas 9990 deg^2 v 8169 deg^2), $F_{1,24} = 11.151$, $p < 0.01$. There were also overall significant difference between quadrants for both the central, $F_{3,72} = 48.202$, $p < 0.0001$, and peripheral fields, $F_{3,72} = 115.114$, $p < 0.0001$. This would be expected given the normal shape of the visual fields in Fig. 3. There was evidence that some quadrants were significantly more different between the two groups than others, with the quadrant by Person (deaf or hearing) interactions being significant in both analyses, for the central field, $F_{3,72} = 8.382$, $p < 0.001$, and for the peripheral, $F_{3,72} = 9.012$, $p < 0.0001$. Fig. 4 shows the area plots as per Experiment 1 with asterisks indicating where *t*-tests showed significant differences between the data from the two groups.

3.4. Testing for a possible role of sign language use

From Figs. 3 and 4 it appears that the greatest difference between the two groups was in the lower quadrants of the visual field corresponding to areas of the retina where the hand movements of signed language would tend to project. Agrafiotis et al. (2006) found that sign language viewers gazed at the facial area and the mouth of sign language presented as a video clip. The authors comment that most of the participants never looked at the hands. The majority of signs were gesticulated in front of the torso therefore peripheral vision in the lower field would be involved in processing these hand movements. Similarly Siple, Hatfield and Caccamise (1978) reported that observers viewing sign language look at the face and can receive sign language signed as far as 70° into the periphery. Muir and Richardson (2005), and Agrafiotis et al. (2006) also suggest that deaf people perceive the face in foveal high resolution, and hand gestures are viewed in peripheral vision at lower resolution. Muir and Richardson (2005) found as much as 90% of fixation time was on the upper face in sign language viewing. Small percentages of viewing time were given to the lower face and occasionally the upper body. Non-foveal vision is vital for sign language perception, but is also used in the viewing

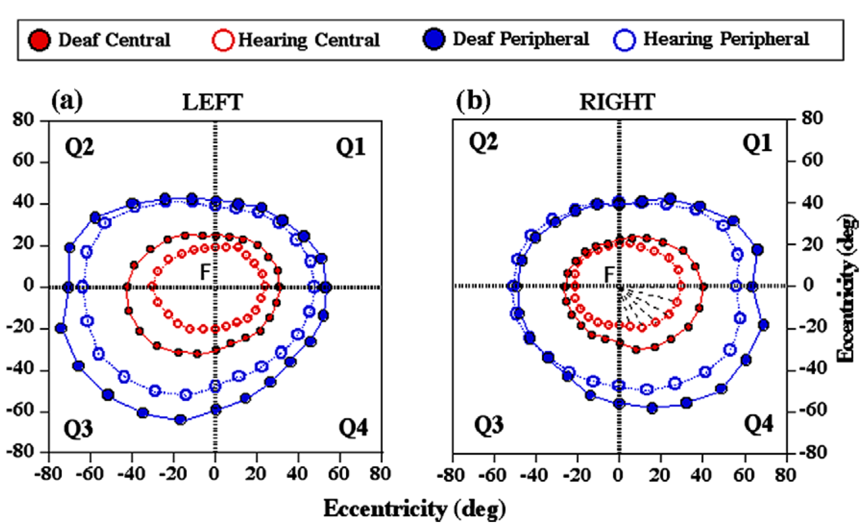

Fig. 3. The mean visual fields of the 13 deaf and the 13 hearing observers. a and b, mean central (red – around 30° from fixation) and peripheral (blue – around 60° from fixation) fields of the deaf (filled symbols) and hearing (open symbols) groups for the left, a, and right eyes, b. Each point indicates the mean location at which a moving spot of light was detected. Again to aid clarity error bars are not shown on this figure but the standard errors for both groups, for both eyes and for both groups were on average about 2.5°. The centre of each graph indicates the fixation point. The grey dashed lines in Fig. 3b, indicate the boundaries of the six triangles that would be used to calculate the area of Quadrant 4 (Q4), in this example for the central field for the hearing observers. The mean central field of the deaf observers was 1493 deg^2 bigger, and the peripheral field was 1822 deg^2 bigger than those of the hearing controls, see Fig. 4. The field size difference between the two groups was most marked in the lower quadrants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

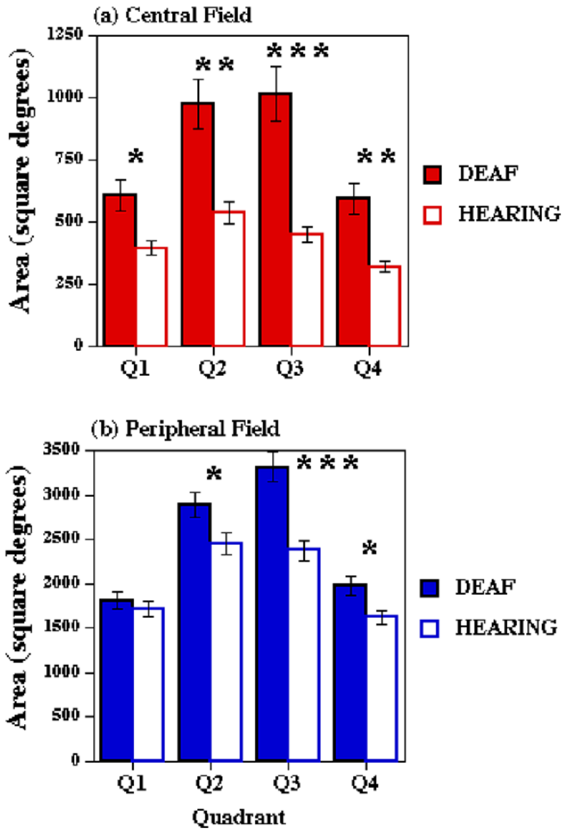

Fig. 4. Column graph, following the same format as Fig. 2, of the mean areas of each quadrant of the visual fields averaged across the left and right eyes for 13 deaf (filled columns) and 13 hearing (open columns). Again note that the quadrant numbers (Q1–Q4) refer to those for the left eye and the mean values include the matching quadrants in the right eye (Q2, Q1, Q4 and Q3, respectively). The asterisks indicate any significant differences between the groups with * indicating $p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

of lip movements and speech reading that both project to the lower visual field. Together these suggest a possible explanation of the better visual performance in the lower visual field if sign language exposure has an influence. At the suggestion of a referee to test this we conducted a further three factor ANOVA combining the upper (Q1 and Q2) and lower (Q3 and Q4) quadrants. The factors were therefore Person (deaf or hearing), eye (left or right) and field (upper or lower). For both the Central and Peripheral data analysis the overall difference between the two groups was, as reported earlier highly significant: for central, $F_{1,24} = 18.825$, $p < 0.001$, for peripheral, $F_{1,24} = 11.488$, $p < 0.001$. The result of interest was the significant Person by Field interactions, for central, $F_{1,24} = 6.090$, $p < 0.05$ and for peripheral, $F_{1,24} = 10.536$, $p < 0.01$. The greatest difference between the two groups was in the lower visual field. For the deaf observers for the central the mean area of the upper field was 1590 deg^2 and for the hearing observers 939 deg^2 a smaller difference than for the lower field, 1616 deg^2 v 774 deg^2. Similarly for the peripheral field the difference is marked, for the upper field, 4697 deg^2 v 4171 deg^2 and the lower field, 5293 deg^2 v 3997 deg^2. Note that the statistics were again performed on the square root of these areas for each individual's data.

To explore whether these differences between the upper and lower field were related to sign language use we analysed the data just from the deaf observers in a series of two factor ANOVAs. Using the data shown in Table 1 we split the deaf group into two groups based on either main language used (BSL $N = 7$ or English $N = 6$) or when they began signing (early $N = 3$, late/never $N = 10$) or cause of deafness (genetic $N = 4$ or not genetic $N = 9$). For both central and peripheral no significant Group differences or interactions were found. The complete analyses are not reported here although it should be noted that for all these analyses the group sizes were small. We also tried to find whether extent of sign language use was correlated with individual field/quadrant areas with inconclusive results, again not reported here. A possible confounding variable was the participant's age, as visual fields tend to reduce in size with age particularly in the upper fields (Q1 and Q2). However, partialling out age in these analyses did not improve the results. The overall conclusion of all this analysis is that no real evidence could be found for sign language use causing the greater changes in the lower visual fields of the deaf observers, but a study with more participants in the different deaf subgroups and including hearing signers would be needed to conclusively rule out this possibility.

3.5. Discussion for deaf observers' data

As can be seen from Figs. 3 and 4 the deaf observers were found to have significantly larger central and peripheral visual fields than hearing controls. The increased sensitivity in deaf observers reported in previous research is therefore supported but now also for previously unexplored locations. Stevens and Neville (2006) found a uniform difference across the visual field of the right eye between deaf observers and hearing controls whereas for both the central and peripheral visual field we found significant Person by quadrant interactions. These arose due to the greatest difference between the two groups occurring in the lower visual field. However the tests described above found no evidence that this could be attributed to the use of sign language in the deaf group.

Previous research has suggested that observers, either deaf or hearing, who started using sign language early in life show a right visual field advantage whereas non-signers show either no difference in fields or a left visual field advantage (Bosworth & Dobkins, 2002; Neville & Lawson, 1987c). This would have shown itself in the results of the main ANOVAs described in Section 3.3 as significant interactions between the Person, eye and quadrant factors. No such significant interactions were found. However this could be due to differences in the stimuli and tasks used in our experiments and the two earlier studies, for example, our small dot stimulus could be considered as providing only very weak motion stimulation when compared to these studies, which used many dots in coherent motion.

During collection of the perimetry data in Experiment 2 the second author noted that deaf observers appeared far better than the hearing controls at maintaining fixation. Recall that the Goldmann perimeter allows the tester to see the observer's eye to check for fixation on the central point. For all 13 deaf observers a total of 18 presentations, and 25 for the hearing controls, had to be repeated due to losses of fixation. Good fixation stability has been shown to lead to improved performance in detecting motion in the periphery (Murakami, 2004) and stability could be improved with experience/training (Di Russo, Pitzalis, & Spinelli, 2003). It is possible that the deaf have learnt to maintain good fixation as a strategy in signed conversation in order to more readily recognise signs, lip movements and facial expressions projecting to their periphery. Alternatively good fixation stability may be needed to best extract any visual information presented in the periphery in all everyday situations. Good fixation stability might therefore partly explain the results we report here and also those of previous studies. Some of the differences between individuals in the deaf group might also be due to differences in fixation stability. However why better fixation stability would result in better performance in the lower visual field is unclear. We are currently testing this further with more objective measures of fixation stability.

Several of the factors mentioned above may be involved in the finding of larger visual fields in the deaf observers. There may also be different reasons why video game players have larger visual fields than the normal population. Indeed the striking difference between the findings of the two experiments was that when comparing deaf and hearing participants the quadrant × Person interaction was highly significant but was not significant when comparing the VGP and NVGP groups. The following comparison of the data from the deaf and VGP participants allowed for some dissociating of the effects described above however note that these two groups were not matched for gender or age.

3.6. Comparison of deaf and VGP data

The data for the VGP and the deaf participants were compared in two separate three factor mixed measures ANOVAs, one for the central field data and one for the peripheral field data. For the central field there were no overall differences between the VGP and deaf groups, $F_{1,21} = 0.163$, n.s. As found earlier the quadrant factor was significant, $F_{3,63} = 16.304$, $p < 0.0001$, and importantly there was a significant quadrant by Person (VGP/deaf) interaction, $F_{3,63} = 3.577$, $p < 0.05$. As can be seen when comparing Figs. 2a and 4a this shows that the distribution of the peripheral field is different in the two groups with the deaf having larger fields in the temporal fields (Q2 and Q3 in the left eye and Q1 and Q4 in the right eye). No other interactions were significant.

In contrast for the peripheral field the deaf observers had overall significantly larger fields than the VGP, $F_{1,21} = 7.379$, $p < 0.05$. Again the quadrant factor was significant, $F_{3,63} = 41.517$, $p < 0.0001$, and importantly there was again a significant quadrant by Person (VGP/deaf) interaction, $F_{3,63} = 9.265$, $p < 0.0001$. As can be seen when comparing Figs. 2b and 4b this shows that the distribution of the peripheral field is different in the two groups with the deaf having larger fields in the temporal fields (Q2 and Q3 in the left eye and Q1 and Q4 in the right eye). No other interactions were significant.

This analysis therefore shows that deafness and video game playing have different effects on the visual fields. VGP players show a more uniform increase in both central and peripheral visual fields. For the central field deaf observers show an increase in field size similar to the VGP group but with a different distribution. In contrast for the peripheral field deaf observers show both a larger field overall but one that shows a similar change in distribution as found for their central field.

3.7. Comparison of the two control groups

At the suggestion of a reviewer to check for homogeneity between data from the control participants of the two experiments two further separate three factor mixed measures ANOVAs, one for the central field data and one for the peripheral field data. These revealed no overall significant differences between these two groups of controls ($F_{1,21} = 0.379$, n.s., and $F_{1,21} = 0.849$, n.s., for the central and peripheral fields respectively). No interactions containing the group factor were significant, highest $F_{3,63} = 1.002$, n.s.) The two groups of controls therefore appear very homogeneous as can also be seen by comparing Figs. 1 and 3 or Figs. 2 and 4.

3.8. Can our findings be explained by reaction time differences?

An alternative explanation of our findings is that they are simply due to reaction time differences between the groups. Because Goldmann perimetry requires the observer to press a button when they detect the target light then an observer who has a quicker reaction times could appear to have larger visual fields than an observer with slower reaction times. We think that such differences are unlikely as an explanation of our findings. The target moved across the field at about $5^\circ\ s^{-1}$, however the mean angular difference between, for example, the VGP and NVGP group's central visual fields were about 6° and a maximum of 10° in some locations. This would mean that reaction time differences would be 1–2 s between the two groups, which is highly unlikely. A similar argument applies for the peripheral field where the mean difference was about 4°. For the deaf observers the angular differences from hearing observers in some parts of the field were as large as 20° with means of nearly 10° which would imply a mean reaction time difference between the two groups of at least 2 s or 4 s in some parts of the field. Again these differences in reaction time seem very unlikely. Indeed in a separate study we have measured the reaction times to lights flashed in the periphery and found that deaf observers are significantly quicker but only by about 100 ms on average, which would correspond only to about 0.5° in angular movement of our targets.

3.9. Analysis of deaf video game players

In Experiment 2 none of the hearing or deaf participants were habitual video game players but, as can be seen from Table 1, 6 of the deaf group did occasionally play video games, one played for up to 4 h a week with the others playing for 1 to 2 h a week. This exposure is small compared to the VGP group in Experiment 1 and Green and Bavelier (2003). Using data just from the deaf participants we conducted two separate three factor mixed measures ANOVAs, one for the central field data and one for the peripheral field. Overall there were no differences between the two subgroups. For the central field, $F_{1,11} = 1.137$, n.s. and for the peripheral field, $F_{1,11} = 0.834$, n.s., no other interactions involving this subgroup factor were significant. The playing of video games seemed to cause no additional change to the size of the visual fields in the deaf participants, however this was from small samples with low video game exposure, was not balanced for other factors and hence may be worthy of further study.

3.10. Discussion

In summary Experiment 1, for video game players, and Experiment 2, for deaf observers, found enhanced performance in Goldmann perimetry when compared to controls. For the video game players, Figs. 1 and 2, the improvement tended to be uniform across the field whereas in the deaf the improvement was most marked in the lower visual field, Figs. 3 and 4. As suggested by the direct comparison of both groups, it is possible that different mechanisms or processes might underlie the improvements in the two groups. If the findings for both groups can be explained by changes in visual attention then, especially for the peripheral field, it seems that deafness and the playing of action video games cause different changes to the distribution of attention.

The role of attention on vision is well documented, and by increasing attention, visual performance can be significantly improved for example, the useful field of view can be extended with training (Ball, Beard, Roenker, Miller, & Griggs, 1988). The playing of action video games may be of benefit to peripheral vision by improving visual attention. Scalf et al. (2007) have shown in a population of elderly adults that practice with the functional field of view task can improve attention by increasing the recruitment of pre-central and the right inferior gyrus. Habitual VGPs may be demonstrating improved peripheral vision as a result of visual training and of redirecting their attention during play by attending more selectively to peripheral visual events. However repeated behaviours are known to affect the cortical mapping, for example, musicians show adaptations to the somatosensory and motor cortices when compared to non-musical controls. Experienced string players show cortical reorganization of the representation of the fingers of the left hand (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Highly skilled pianists exposed to a novel tapping task show a rapid increase in M1 (primary motor cortex) activation (Hund-Georgiadis & von Cramon, 1999). Also just 2 h daily training over 5 days in musically naïve subjects is enough to see changes in the cortical motor areas (Pascual-Leone, 2001) therefore habitual computer game playing may lead to increased activation of the visual cortical areas. It is also known that visual stimuli activate the redundant auditory cortex of deaf individuals which may account for some of the enhanced performance of our deaf population (Finney, Fine, & Dobkins, 2001). However, for the VGPs, it is unlikely that the auditory cortex will be involved in vision, their better peripheral performance may have to be supported by other mechanisms and neural substrate such as the parietal lobe.

Our findings for our deaf observers are also consistent with a wider literature that has shown better performance in a spared modality in those who have lost a modality, for example blind participants are better at localising sound sources in space particularly in the auditory periphery (Lessard, Pare, Lepore, & Lassonde, 1998; Voss et al., 2004). Studies have shown that early loss of a modality is more 'beneficial' than late loss both in the deaf and in the blind (Roder, Rosler, & Spence, 2004) but not always, (Voss et al., 2004). The heterogeneous nature of our deaf group did not allow us to test directly whether the deaf improvement in field sizes is due to loss of a modality or the visual stimulation of sign language. Also, given what is known about normal and abnormal visual development (see Atkinson, 1995, for a review) and how early experience can affect later visual capabilities (Maurer, Lewis, & Mondloch, 2005) it is of interest to know what effect deafness has on visual development (Netelenbos & Savelsbergh, 2003).

Goldmann perimetry is commonly used to assess a patient's visual field in UK eye clinics and an implication from our findings is that if the fields of both video game players but especially the deaf are of 'normal' size then this may actually be indicative of field restrictions. This may have implications for early detection of degenerative conditions that reduce the visual field such as retinitis pigmentosa. Indeed, as can be seen from Fig. 3, for a deaf observer's field to have receded to that of the normal controls could mean the actual loss of a significant proportion of their typical visual field which might begin to compromise their main channel of communication. This would probably be true of all the range of types of deaf observers we have tested, see Table 1.

We found no overall significant difference in the size of the central Goldmann field between the deaf and VGP groups and this might suggest that the same changes in attentional mechanisms underlie this advantage in both groups. However the distribution of these fields depended significantly on group. Also the peripheral Goldmann field was found to be significantly larger overall in participants who are deaf with largest differences occurring in the lower regions of the visual field. Although these regions would be most stimulated by sign language viewing our data analysis could find no support for sign language use influencing the size of visual fields in the deaf observers. The effects of auditory deprivation are well reported at the cortical level, with sign language and speech viewing activating areas of A1 and A2 (Paulesu & Mehler, 1998, but see Bavelier et al., 2006). Little is known about the effect of deafness on the rest of the visual anatomy, and the cortical re-mapping in response to auditory deprivation could be affecting adaptation to the more anterior visual pathway, to allow for the deaf visual advantage in extreme peripheral vision that we have observed here (Doucet, Bergeron, Lassonde, Ferron, & Lepore, 2006; Giraud, Price, Graham, Truy, & Frackowiak, 2001).

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