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Interactive report

Visual contrast sensitivity in deaf versus hearing populations: exploring the perceptual consequences of auditory deprivation and experience with a visual language[1]

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Abstract

Early deafness in humans provides a unique opportunity to examine the perceptual consequences of altered sensory experience. In particular, visual perception in the deaf may be altered as a result of their auditory deprivation and/or because the deaf rely heavily upon a visual language (American Sign Language, or ASL, in the US). Recently, we found that deaf, but not hearing, subjects exhibit a right visual field/left hemisphere advantage on a low-level direction of motion task, a finding that has been attributed to the deaf's experience with ASL [Psychol. Sci. 10 (1999) 256; Brain Res. 405 (1987) 268]. In order to determine whether this visual field asymmetry generalizes to other low-level visual functions, in this study we measured contrast sensitivity in deaf and hearing subjects to moving stimuli over a range of speeds (0.125–64°/s). We hypothesized that if ASL use drives differences between hearing and deaf subjects, such differences may occur over a restricted range of speeds most commonly found in ASL. In addition, we tested a third group, hearing native signers who learned ASL early from their deaf parents, to further assess whether potential differences between groups results from ASL use. These experiments reveal no overall differences in contrast sensitivity, nor differences in visual field asymmetries, across subject groups at any speed tested. Thus, differences previously observed between deaf and hearing subjects for discriminating the direction of moving stimuli do not generalize to contrast sensitivity for moving stimuli, a result that has implications for the neural level at which plastic changes occur in the visual system of deaf subjects. © 2001 Elsevier Science B.V. All rights reserved.

Theme: Neural basis of behavior

Topic: Neural plasticity

Keywords: Cross-modal; Plasticity; Deaf; Psychophysics; Visual

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1. Introduction

The ability of the developing brain to reorganize itself in response to altered sensory input, a phenomenon referred to as 'plasticity', has been well documented in the animal literature. Many early studies focused on the neural changes that occur in response to raising an animal with restricted input to one sensory modality. For example, raising animals (cats and monkeys) with monocular lid suture [27,74], or in an environment containing restricted visual information [15,53,72], results in substantial changes in the organization and selectivities of neurons in visual cortex (see Refs. [28,42,77] for a review).

In addition to studies that restrict sensory input within a modality, there also exists a large animal literature documenting the neural changes that occur as a result of removing one sensory modality entirely, referred to as 'cross-modal' plasticity (see Refs. [57,77,79] for review). For example, in cats blinded at birth [31,59] and cats and ferrets deafened at birth [52,60], cortical areas that would normally be devoted to the deprived modality instead come to respond to the other intact senses. As further evidence that primary sensory areas are quite flexible in their ability to respond to input from modalities other than their own, several studies have shown that visual input can be re-routed to the classically defined auditory cortex (in ferrets), producing neurons in this area that are instead responsive

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to visual stimuli ([65,66,73,78], and also Refs. [22,41] for similar findings for re-routing between retina and somatosensory cortex in hamsters). In sum, a wealth of data from animal studies suggests that the developing brain can reorganize itself in response to altered sensory input. However, obtaining behavioral data from animals is difficult, and thus only a handful of studies have tested whether these neural changes are accompanied by enhanced or altered perceptual abilities [30,58,81].

In humans, the study of blind or deaf subjects affords the opportunity to investigate the perceptual consequences of modality-specific sensory deprivation [33]. Consistent with the animal literature, the results from such studies generally suggest that lack of input to one modality leads to enhanced representation of the intact modalities. For example, compared to sighted subjects, blind people possess superior tactile discrimination (Ref. [4] but cf. Refs. [13,68]) and auditory localization (Refs. [36,45,64], but cf. Ref. [82]) abilities. A possible neural basis for these perceptual findings has been provided in brain imaging studies. Results from positron emission tomography (PET) [68,80,82], electroencephalography (EEG) [32,63,67] and magnetoencephalography (MEG) [34] have demonstrated responses to tactile or auditory stimuli in visual cortex of blind subjects. As evidence that this cortical reorganization serves a functional role, Cohen and colleagues [13] showed that disruption of occipital lobe function in the blind (via transcranial magnetic stimulation) impairs their tactile discrimination. In sum, results from blind humans suggest that visual cortex may come to serve other sensory modalities (i.e., tactile or auditory) when deprived of its normal (i.e., visual) input.

In deaf subjects, perceptual and neural imaging studies have similarly been conducted in order to investigate the potential for cross-modal plasticity. Like the pattern of results observed in the blind for visual areas, visual evoked potentials (VEPs) in the deaf reveal enhanced responses over anterior temporal (possibly auditory) areas as compared to hearing subjects [50,51]. (Note, however, that these VEPs may also have arisen from nearby multimodal or visual areas, e.g., superior temporal sulcus). Results from MEG have yielded mixed results. While one MEG study reported responses to vibrotactile stimuli in auditory cortex of a deaf subject [37], another MEG study, in conjunction with functional magnetic resonance imaging (fMRI), conducted in a deaf subject found no evidence for either tactile or visual responses in auditory cortex [26]. Thus, unlike the consistent story that has developed from studies of the blind, the issue of whether classically defined auditory areas in deaf individuals come to serve the other intact senses is still a matter of some debate.

With regard to the visual perceptual abilities of deaf subjects, most studies have focused on higher-level, ‘visual-cognitive’ performance. In this domain, deaf subjects have been shown to exhibit enhanced capabilities along the dimensions of facial processing [3,40], spatial construction and transformation of objects [2], mental transformation, imaging, and rotation [18–20], and gestalt completion [75]. In general, these abilities are thought to be the result of ASL experience, which relies heavily on such cognitive and visuospatial abilities. One common way to ascertain whether enhanced abilities in deaf subjects are due to their experience with ASL, as opposed to their deafness per se, has been to use a third comparison group, referred to as ‘Hearing Offspring of Deaf’ (HOD). HODs are hearing persons who are fluent users of ASL because they were born to deaf signing parents and learned ASL at the same age as deaf subjects with deaf parents. That is, HODs have the same ASL experience as the deaf yet can hear normally. Supporting the notion that ASL experience in the deaf is responsible for their enhanced visual-cognitive abilities, many of the studies mentioned above have shown that HODs, like the deaf, exhibit superior abilities.

Several studies have also investigated aspects of vision in the deaf that are more low-level in nature. Unlike the findings for higher-level tasks, the results from these low-level studies have produced mixed results. For example, deaf and hearing subjects have been shown to perform comparably on tasks such as brightness discrimination [10], shape identification [62][2], temporal discrimination [43], and temporal resolution [11,55]. However, other studies have demonstrated significant differences between groups with respect to relative performance in different parts of the visual field (i.e., visual field asymmetries). For example, Neville and Lawson [50] found that deaf subjects are faster and more accurate than hearing subjects at judging the direction of apparent motion when stimuli are presented in the periphery, but that the two groups perform comparably in the central visual field. This relative peripheral visual field enhancement in the deaf has also been found by Loke and Song [39] in a reaction time task, and by Bosworth and Dobkins [8] in a direction of motion task. A potential neural basis for these perceptual results has been revealed in neural imaging studies. Results from VEP [51], fMRI [1], and MEG [21] all demonstrate selective enhancement of responses to peripheral, but not central, visual field stimuli in deaf signers as compared to hearing controls.

In addition to central/peripheral visual field differences observed between deaf and hearing subjects, other studies have found differences between groups with respect to the relative sensitivity for right (RVF) vs. left visual field (LVF) stimuli. In the study by Neville and Lawson [50] described above, deaf subjects exhibited a RVF over LVF advantage for the detection of apparent motion. Hearing subjects, by contrast, exhibited a slight LVF advantage, results also found in concomitant VEP studies. Based on

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[2] In this study, deaf subjects were faster, yet less accurate, than hearing subjects, suggesting a speed-accuracy tradeoff. Thus, the results from this study do not provide clear evidence for differences in overall performance between deaf and hearing subjects.

the contralateral organization of visual system projections, these results imply differential hemispheric advantages in deaf vs. hearing subjects, with a left hemisphere specialization for motion processing in the deaf. These investigators suggested that, because ASL comprehension is highly dependent on the ability to process moving hand signals, perhaps the left, language-dominant hemisphere has usurped some of the motion-processing functions normally mediated by the right hemisphere. In support of the role of ASL in this visual field asymmetry, Neville and Lawson [49] also found a RVF/left hemisphere advantage in HOD subjects. It should be pointed out, however, that Neville and Lawson's interpretation of their results is somewhat confounded by their choice of stimuli and task. Specifically, their two-frame apparent motion stimulus allowed for the use of position-based, as opposed to motion-based, mechanisms for directional discrimination, an issue that has been widely addressed in the motion literature (e.g., see Ref. [46]). Thus, the observed superior performance in the deaf could be a result of heightened position or motion processing.

Recently, we investigated the issue of left vs. right visual field asymmetries using stimuli designed to isolate elementary motion processing mechanisms while eliminating the use of position and orientation cues. This stimulus consisted of a moving dot display, in which a proportion of dots moved in a coherent fashion (leftward or rightward) while the remaining dots moved in random directions. Although deaf and hearing subjects were found to perform comparably on this task in terms of absolute thresholds and reaction times, we found differences between groups in their relative performance for LVF vs. RVF stimuli. In agreement with the earlier results of Neville and Lawson, hearing subjects in our study exhibited a slight LVF advantage, whereas deaf and HOD subjects exhibited a strong RVF advantage [5,7,8]. Such results confirm a left hemisphere advantage for motion processing in deaf and HOD signers. Most recently, a potential neural basis for these perceptual findings has been reported by Bavelier and colleagues in an fMRI study. Using a moving dot stimulus similar to that employed in our previous psychophysical experiments (with the important exception that stimuli were full-field rather than lateralized to the LVF or RVF), these investigators found that deaf signers exhibited larger responses in motion area MT in the left (as compared to the right) hemisphere of the brain [1].

It remains unclear why deaf and hearing differ for some, but not all, low-level visual tasks. The RVF/left hemisphere advantage for motion discrimination in both deaf and HOD subjects suggests that visual field asymmetries are driven by ASL use. If this hypothesis is correct, hemifield asymmetries may be apparent only for moving stimuli that fall within the range of speeds most commonly found in ASL. To determine: (1) whether deaf and hearing differ on another low-level visual task, contrast sensitivity (the amount of contrast required to see a moving black/white grating presented on a gray background); (2) whether the visual field asymmetry found for motion discrimination generalizes to this contrast sensitivity task; and (3) whether potential differences in contrast sensitivity between deaf and hearing are evident only for the range of speeds most commonly observed in ASL, we measured contrast detection thresholds in deaf, hearing, and HOD subjects over a wide range of speeds. Subjects were tested in the central visual field and in the four peripheral quadrants of visual space: superior left, superior right, inferior left, inferior right. Three different visual field asymmetries were analyzed: (1) central vs. peripheral visual field; (2) right vs. left visual field; and (3) superior vs. inferior visual field. In contrast to the differences found between deaf and hearing subjects for direction of motion discrimination tasks, the results of the present experiments revealed neither differences in overall contrast sensitivity, nor differences in visual field asymmetries across subject groups. This lack of differences on a simple contrast sensitivity task suggests that neither deafness, nor ASL use, alters this aspect of low-level visual perception.

2. Materials and methods

2.1. Subjects

Thirty-four subjects participated in these experiments. Thirteen were deaf signers of American Sign Language (ASL), all of whom had an 80 decibel (dB) loss or greater in both ears. Ten of these subjects were congenitally deaf (eight from genetic inheritance and two from maternal rubella). The three other deaf subjects became deaf by age 2 years (one from meningitis, the other two from an unknown illness). Five deaf subjects began learning ASL in early infancy because they were born to deaf parents, two learned ASL by age 2 years from deaf older siblings. The remaining six learned ASL from friends or teachers, three by age 3 years, and three by age 5 years.

Fourteen of our subjects had normal hearing and no ASL experience. Seven subjects were 'Hearing Offspring of Deaf Parents' (HODs), who signed from birth. HODs were used as a comparison group to determine whether differences observed between deaf and hearing subjects are due to the deaf's auditory deprivation or to their experience with a visual language.

All subjects had normal or corrected-to-normal vision, were right-handed, and were naive to the purpose of the experiment. Deaf and HOD subjects were recruited from the San Diego deaf community. Hearing subjects were recruited from UC San Diego's student population. The mean ages of the three subject groups were: deaf: 30.1±8.0 years, hearing: 24.5±6.0 years, HODs 21.0±9.5 years. Although the mean age of deaf differed significantly from that of HODs ($P<0.05$), age did not correlate significantly with performance and thus will not be considered further.

2.2. Apparatus

Visual stimuli were generated on a Nanao F2-21 video monitor (21 in. display, 1024×768 pixels, 105 Hz) driven by a Cambridge Research Systems (CRS) Video Board. The 15-bit video board allowed for 32,768 discrete luminance levels. The maximum output for the monitor was calibrated to equal energy white (CIE chromaticity coordinates=0.333, 0.333), and the voltage/luminance relationship was linearized independently for each of the three guns in the display, using a Gamma Correction System ('OptiCal 265M', purchased from CRS).

2.3. Stimuli

The stimuli in these experiments were black/white, moving sinusoidal gratings, presented on a gray background field (Fig. 1). Gratings were horizontally oriented and subtended 4° of visual angle. The mean luminance of the gratings and the background field was 28 cd/m^2, with chromaticity coordinates of 0.333, 0.333. The luminance contrast (i.e., the luminance difference between the light and dark phases of the grating) is described in terms of Michelson contrast: (Luminance$_{max}$–Luminance$_{min}$)/(Luminance$_{max}$+Luminance$_{min}$). Note that zero percent luminance contrast refers to a uniform gray field, which is indistinguishable from the background. To assess sensitivity over a range of speeds, gratings were presented at 15 different combinations of spatial and temporal frequency — three spatial frequencies (0.5, 2, and 9 cycles/degree) and five temporal frequencies (1, 4, 8, 16, and 32 cycles/s, or Hz) — comprising a range of speeds from 0.125 to 64°/s [speed (degrees/s)=temporal frequency (cycles/s) divided by spatial frequency (cycles/degree)].

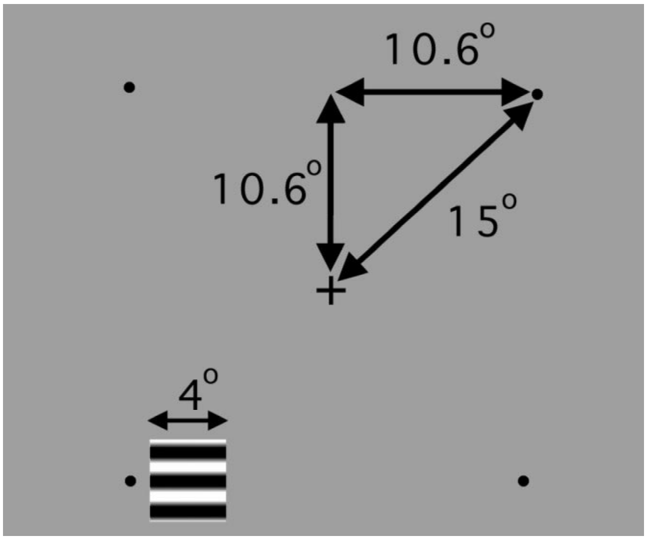


Fig. 1. Upwardly moving black and white sinusoidal gratings were presented on a uniform gray field in one of five visual field locations, indicated either by the fixation cross (+), or by one of four peripheral field markers (●). Peripheral markers were 15° eccentric from fixation. Stimuli appeared randomly to the right or the left of one of the five markers, and subjects were required to respond 'right' or 'left' by pressing one of two keys on a button box (two-alternative forced choice; see Methods for details). For the stimulus configuration shown, the correct answer is 'right.'.

2.4. Contrast sensitivity paradigm

Subjects were tested in a dark room and viewed the video monitor binocularly from a chin rest situated 57 cm away. Subjects were instructed to maintain fixation on a small black cross (length and width=0.5°) in the center of the monitor, and respond via key-presses on a response box. No feedback was provided. On each trial, the grating stimulus appeared randomly in one of five visual field locations: one central (C) location and four peripheral (P) locations. The peripheral locations were superior left (SL), superior right (SR), inferior left (IL), and inferior right (IR), and were centered 15° eccentric from fixation (horizontal eccentricity=±10.6°, vertical eccentricity=±10.6°, see Fig. 1). Visual markers were placed at each of the five potential locations. For peripheral fields, the marker consisted of a small black dot (diameter=0.5°). For the central location, the fixation cross served as the marker.

At the onset of each trial, the grating stimulus appeared centered 2.5° to the left or right of one of the five markers (Fig. 1). The stimulus was presented for a total of 300 ms, with contrast ramped on and off within the first and last 100 ms. At the end of the trial, subjects reported whether the stimulus appeared to the 'left' or 'right' of the marker (two-alternative-forced-choice). Note that subjects did not know beforehand which visual field would contain the stimulus. Thus, they were required to keep their attentional focus broad, in essence, inspecting all five visual fields at the same time.

Contrast sensitivity was determined using a Best-PEST staircase procedure [38]. Specifically, this algorithm determines a contrast threshold, defined as the luminance contrast required to yield 75% correct performance. Contrast sensitivity is defined as the inverse of contrast threshold (i.e., sensitivity=1/threshold). For each stimulus condition tested, the staircase procedure continued until the subject had satisfied a 50% confidence criterion or a maximum of 200 trials, which we have previously shown to provide reliable estimates of sensitivity [16].

Contrast sensitivity values were obtained for the 15 different combinations of spatial and temporal frequency (see above), with testing divided into three different blocks. Each block contained one spatial frequency, all five temporal frequencies, and all five visual field locations, for a total of 25 stimulus conditions per block. Thus each subject provided a total of 75 contrast sensitivity values (three spatial frequencies×five temporal frequencies×five locations). A total of 5–8 h were required to complete the entire experiment.

2.4.1. Potential for eye movements

The importance of maintaining fixation was emphasized throughout the course of the experiment. Because we could not rule out the possibility that some subjects would nonetheless attempt to break fixation in order to look directly at the peripheral stimuli, our paradigm was designed to minimize the potential for eye movements in two ways. First, subjects could not predict which of the five visual field locations would contain the stimulus, precluding attempts to re-direct fixation before the onset of a trial. Second, the short duration of the stimulus (300 ms) in comparison with the relatively long latencies for eye movements (~250–300 ms, [24,70,71]) helped to ensure that the stimulus offset occurred before any eye movement could be initiated.

2.5. Data analysis

The speed of ASL signs falls within a restricted range (for a five foot viewing distance, range=10–25°/s, mean (±standard deviation)=16±9.7°/s, [9]). If experience with ASL influences low-level visual perception, we hypothesized that differences in contrast sensitivity across groups may exist over the restricted range of speeds found in ASL. Spatial and temporal frequency data were thus combined to create nine different speeds (0.125, 0.5, 1, 2, 4, 8, 16, 32, and 64°/s), which included the range of speeds most prevalent in ASL signs.

Differences in contrast sensitivity across the three subject groups were analyzed in two main ways. First, we investigated differences in absolute contrast sensitivity. This allowed us to determine if any of our subject groups exhibited overall better performance than the others, and whether such differences existed only for a restricted range of speeds. Statistical analyses of the data were conducted using repeated measures analysis of variance (ANOVAs). Since contrast sensitivity is known to be better in the center, as compared to the peripheral, visual fields, analyses were conducted separately on central and peripheral data. For the central location, ANOVA factors were: three subject groups (deaf, hearing, and HOD) and nine speeds (0.125, 0.5, 1, 2, 4, 8, 16, 32, and 64°/s). Similarly, for peripheral locations, factors were subject group and speed, with the added factor of four stimulus locations (superior right (SR), inferior right (IR), superior left (SL), and inferior left (IL)).

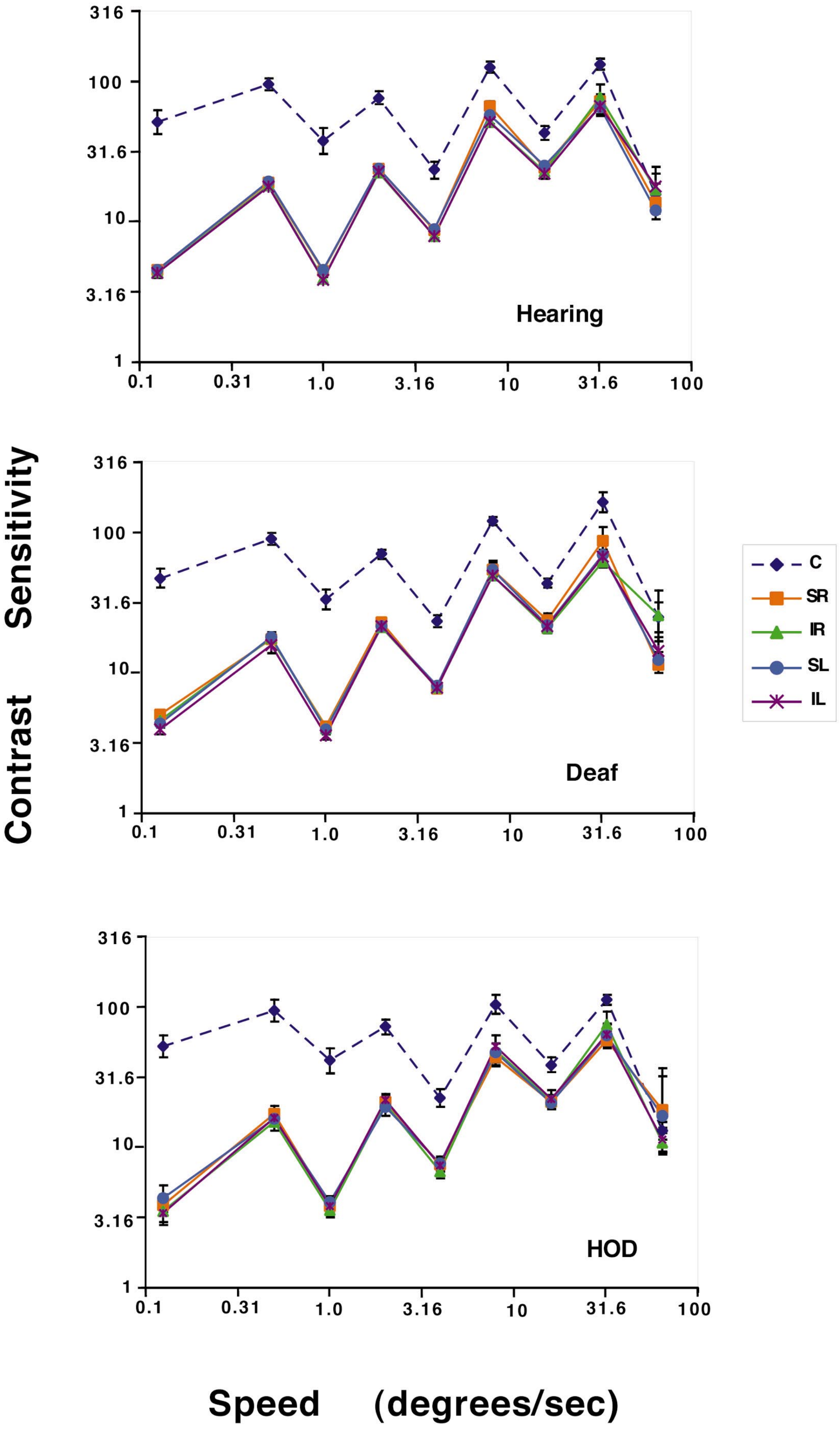
Second, we investigated differences in visual field asymmetries across subject groups. To this end, we determined visual field ratios for each subject before conducting our statistical analyses. Three visual field asymmetries were analyzed. (1) Central (C) vs. Peripheral (P) Asymmetry. Here, the subject's contrast sensitivity for the central stimulus was divided by the subject's mean sensitivity averaged across the four peripheral field stimuli, i.e., SR, SL, IR, and IL. The resulting ratio is described as C/P. (2) Right Visual Field (R) vs. Left Visual Field (L) Asymmetry. Here, the mean sensitivity averaged across SR and IR locations was divided by the mean sensitivity averaged across SL and IL locations, resulting in a R/L ratio. (3) Superior Visual Field (S) vs. Inferior Visual Field (I) Asymmetry. Here, the mean sensitivity for SR and SL locations was divided by the mean sensitivity for IR and IL locations, resulting in a S/I ratio. The three contrast sensitivity ratios, C/P, R/L and S/I, were analyzed in a repeated measures ANOVA with subject group (3), spatial frequency (3), temporal frequency (5) and visual field (2, e.g., right visual field vs. left visual field) as factors.

Note that log values were used for all analyses, since log, but not linear, contrast sensitivity data are known to conform to normal distributions [16]. Accordingly, all group mean data are presented in terms of geometric means.

3. Results

3.1. No differences in absolute sensitivity across subject groups as a function of stimulus speed

Group mean contrast sensitivity data from each of the three subject groups (deaf, hearing and HODs) are plotted as a function of speed (0.125–64°/s) in Fig. 2, separately for each of the five visual field locations. Data plotted as a function of speed do not yield smooth functions, since contrast sensitivity is known to be dependent on the temporal frequency, and not the speed, of a moving stimulus [12,29]. Deaf, hearing, and HOD subjects performed comparably on both central ($F(2)=0.1$, $P=0.89$) and peripheral ($F(2)=0.5$, $P=0.62$) stimuli, indicating that neither deafness, nor sign language use, leads to overall increases or decreases in absolute contrast sensitivity. For peripheral locations, no interaction between subject group and speed was found ($F(16, 248)=0.11$, $P>0.99$), indicating that ASL use did not lead to differences between signers and non-signers over a specific range of speeds. However, for central data, there was a significant two-way interaction of subject group*speed ($F(16, 248)=1.7$, $P<0.05$), which appeared to be driven by worse performance of HODs at higher speeds. It is not obvious why HODs would differ from the other groups along this dimension, and only for central but not peripheral locations. Indeed, when HODs were excluded from the analysis, this interaction became non-significant. Since there is no theoretically compelling reason to believe that HODs truly differ from the other groups for this particular stimulus condition, and the effect is only barely significant ($P=0.045$), we believe this interaction to be due to chance and will not consider it further here. In conclusion, neither auditory deprivation nor ASL experience leads to overall increases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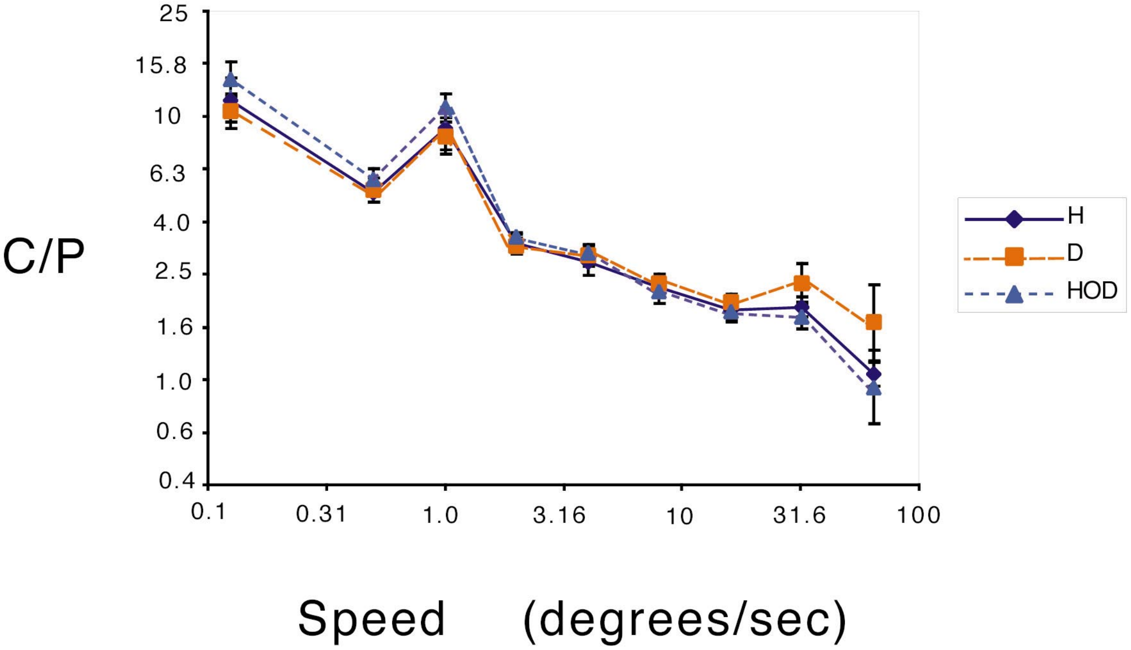

Fig. 3. Central visual field/peripheral visual field (C/P) ratios for hearing (H), deaf (D), and hearing of deaf (HOD) subject groups is plotted as a function of speed. Subject groups do not differ in sensitivity to central versus peripheral visual field stimuli, at any speed tested. Error bars represent standard errors of the means.

or decreases in contrast sensitivity in deaf as compared to hearing control subjects, even within the range of speeds (i.e., 10–25°/s, [9]) commonly found in ASL signs.

3.2. No differences in visual field asymmetries across subject groups as a function of speed

Although we found no absolute differences in performance across subject groups, it is nonetheless possible that subject groups differ in terms of visual field asymmetries. To investigate this, we conducted separate statistical analyses on visual field ratios (see Methods for details): Central Visual Field/Peripheral Visual Field (C/P), Right Visual Field/Left Visual Field (R/L) and Superior Visual Field/Inferior Visual Field (S/I). It is possible that grouping data in this way might reveal visual field asymmetries not apparent with data separated, as above, into five different locations.

3.2.1. Central/peripheral (C/P) visual field ratios

Results from previous perceptual and neural imaging studies suggest that deaf subjects may perform better than hearing subjects when stimuli are placed in the peripheral, rather than the central, visual fields (see Introduction). To investigate whether a similar trend exists for contrast sensitivity, we compared C/P ratios across subject groups. Group mean C/P ratios are plotted as a function of speed in Fig. 3. As expected, C/P ratios were found to be significantly greater than 1.0 ($F(1)=539.5$, $P<0.0001$), indicating better performance in the central, as compared to the peripheral, visual field. In addition, there was a strong effect of speed on C/P ratio ($F(8)=106.7$, $P<0.0001$), resulting from a large central field advantage at slow speeds (~12-fold at 0.125°/s), and a smaller central field advantage at higher speeds (~1.2-fold at 64°/s), indicating that the peripheral visual fields are relatively specialized for fast-moving stimuli. With regard to group differences in the effect of speed on C/P ratios, however, no main effect of subject group was observed ($F(2, 31)=0.2$, $P=0.80$), nor was a significant interaction found ($F(16, 248)=1.1$, $P=0.38$). These data indicate that neither deafness, nor ASL experience, leads to relative enhancement of contrast sensitivity in the peripheral versus central visual fields, at any speed tested.

3.2.2. Right visual field/left visual field (R/L) ratios

In addition to differences in central vs. peripheral processing, perceptual and neural imaging studies have reported that deaf subjects perform better on a motion task in their right visual field, as compared to their left visual field (whereas hearing subjects show an opposite trend). In order to determine whether the right visual field advantage

Fig. 2. Mean contrast sensitivity for hearing, deaf, and hearing of deaf (HOD) subject groups is plotted as a function of speed, separately for each visual field location. Hearing, deaf, and HOD do not differ in contrast sensitivity at any speed tested. Legend at right applies to all three graphs. C=center, SR=superior right, IR=inferior right, SL=superior left, IL=inferior left. Error bars represent standard errors of the means.

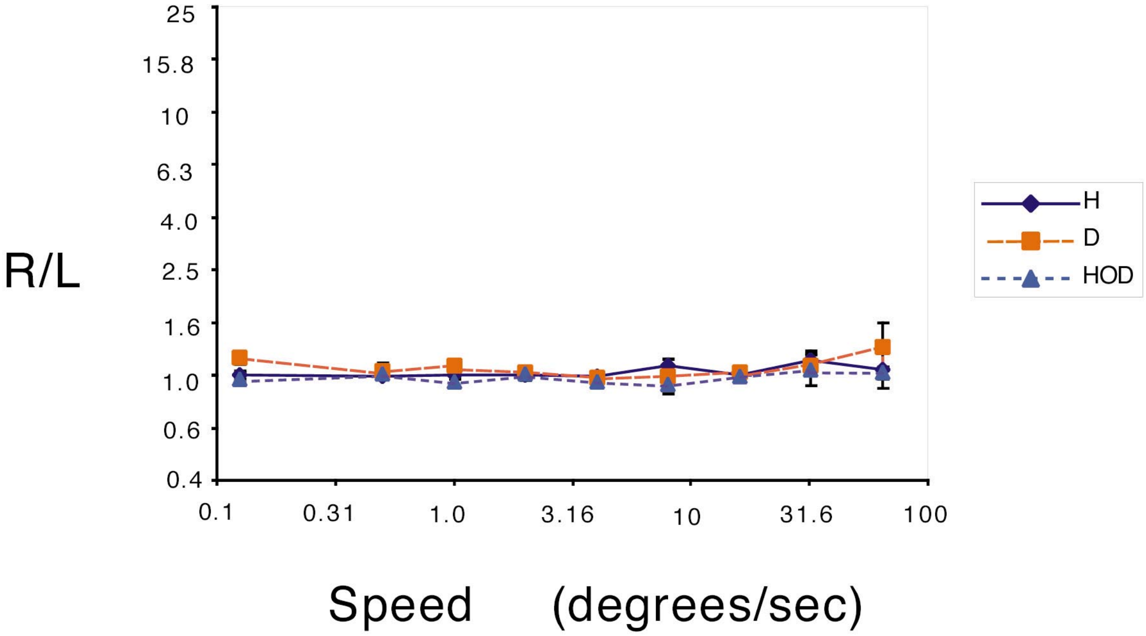

Fig. 4. Right visual field/left visual field (R/L) ratios for hearing (H), deaf (D), and hearing of deaf (HOD) subject groups is plotted as a function of speed. Subject groups do not differ in sensitivity to right versus left visual field stimuli, at any speed tested. Error bars represent standard errors of the means.

in the deaf for motion discrimination generalizes to simple contrast detection, we compared R/L ratios across subject groups. Group mean R/L ratios are plotted as a function of speed in Fig. 4. Here, a R/L ratio greater than 1.0 indicates better performance in the RVF (i.e., a RVF advantage), while a value less than 1.0 indicates a LVF advantage. We found no overall differences in performance for RVF vs. LVF stimuli, i.e., ratios were not significantly different from 1.0 ($F(1)=1.7$, $P=0.20$). In addition, there was no main effect of speed on R/L ratios ($F(8)=1.0$, $P=0.44$). Finally, deaf, hearing, and HOD subjects performed comparably across the right and left visual fields, ($F(2, 31)=$

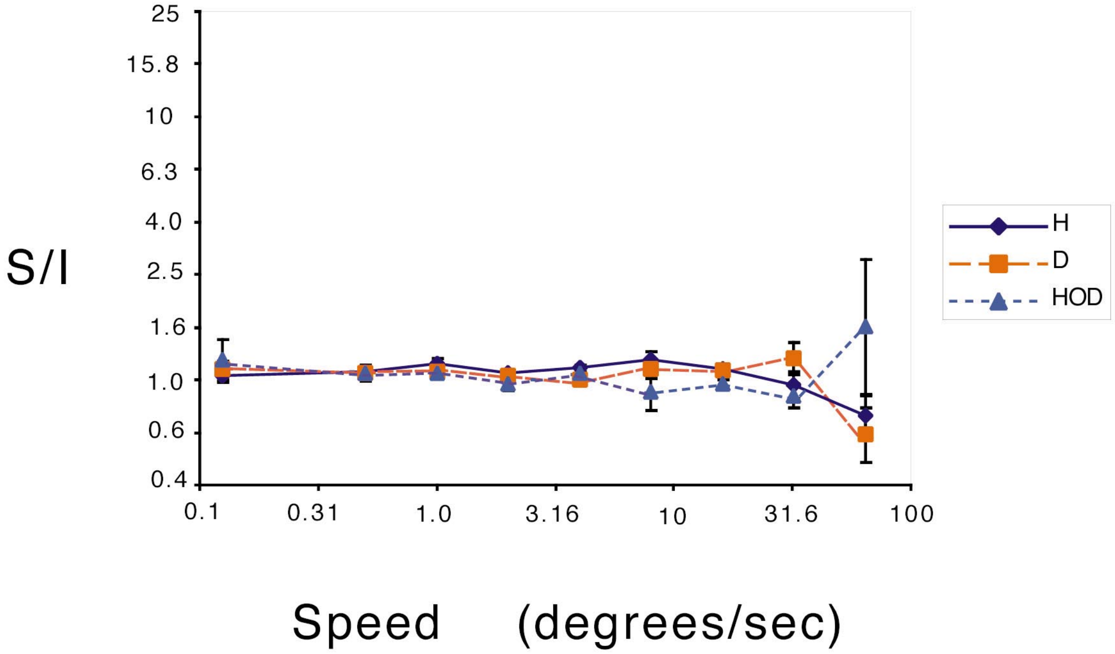

Fig. 5. Superior visual field/inferior visual field (S/I) ratios for hearing (H), deaf (D), and hearing of deaf (HOD) subject groups is plotted as a function of speed. Subject groups do not differ in sensitivity to superior versus inferior visual field stimuli, at any speed tested. Error bars represent standard errors of the means.

1.4, $P=0.27$), with no significant interactions between subject group and speed ($F(16, 248)=0.5$, $P=0.96$). Thus, the right visual field advantage observed in the deaf for motion discrimination does not appear to generalize to simple contrast sensitivity for moving stimuli, even at speeds most commonly found in ASL signs.

3.2.3. Superior/inferior visual field (S/I) ratios

Because signers fixate on each other's faces while conversing in ASL, most ASL signs fall in the viewer's inferior visual field. Consequently, ASL use may lead to selective improvements in this region of space. To test this, we compared S/I ratios across subject groups. Group mean S/I ratios are plotted as a function of speed in Fig. 5. Here, a S/I ratio greater than 1.0 indicates a SVF advantage, while a value less than 1.0 indicates an IVF advantage. As with R/L ratios, there were no overall differences in performance for SVF vs. IVF stimuli, i.e., ratios were not significantly different from 1.0 ($F(1)=1.2$, $P=0.28$), and there was no main effect of speed on S/I ratios ($F(8)=0.8$, $P=0.61$). Similarly, deaf, hearing, and HOD subjects performed indistinguishably in the superior and inferior visual fields ($F(2, 31)=0.143$, $P=0.87$). However, a significant interaction of speed*subject group was found ($F(16, 248)=2.5$; $P<0.002$), which again depended on the inclusion of HODs in the analysis. Indeed, this interaction became non-significant when HODs were removed. Thus, our data do not support differences between deaf and hearing subjects in the relative performance in superior vs. inferior visual fields.

In sum, the results of this contrast sensitivity analysis do not support differences between hearing and deaf groups in overall contrast sensitivity or visual field asymmetries, even for the range of speeds most commonly found in ASL signs.

4. Discussion

The purpose of these experiments was to provide further investigation of potential differences between deaf and hearing subjects in low-level visual perception. Because we found no differences between subject groups on our contrast sensitivity task — either in terms of absolute sensitivity or visual field asymmetries — at any speed, we conclude that the auditory deprivation and ASL experience of the deaf do not lead to substantive changes in structure or function at early stages of sensory processing. Thus, these null findings suggest that the previously reported differences between deaf and hearing on higher-level visual-cognitive tasks (such as facial recognition, mental rotations, and gestalt completion) are unlikely to be attributable to an overall enhancement of low-level sensitivity in the deaf. Rather, such effects most likely reflect neural changes in higher-level brain regions that are specialized for those particular functions.

Several potential factors could have led to our null results. First, our range of stimulus parameters might have been too narrow. Although this is unlikely to be the case, since our stimuli spanned a wide range of speeds (0.125–64°/s, including those most commonly found in ASL), we cannot rule out the possibility that deaf and hearing might differ outside this range. Second, there is the potential for subjects to have moved their eyes in an attempt to look directly at the peripherally placed stimuli. Although we took precautions to prevent such occurrences (see Methods), we cannot rule out their existence altogether. If one group tended to 'cheat' more than the others, this could potentially mask differences between groups. For example, imagine that deaf subjects actually possess higher contrast sensitivity than hearing subjects. If only hearing subjects consistently break fixation on this task, their estimated sensitivity would be an overestimation of their true performance, and put them (seemingly) on a par with the deaf. However, there is no reason to suspect differences across subject groups in eye movements, making this factor highly unlikely to account for our results. Finally, if deafness or ASL use produces only small changes in contrast sensitivity, differences between deaf and hearing subjects might become apparent only for larger sample sizes than used here. However, other studies have found significant differences between deaf and hearing subjects using a comparable number of subjects as in the present study.

4.1. Visual field asymmetries

Differential visual field sensitivity has been addressed in several previous studies of vision in the deaf. To date, experiments have focused on central vs. peripheral and left vs. right visual field asymmetries. In this study, we investigated these effects, as well as superior vs. inferior visual field asymmetries, for contrast sensitivity.

4.1.1. Central vs. peripheral

In previous experiments, it is generally the case that subjects (both hearing and deaf) perform better on visual tasks in the central than in the peripheral visual fields. However, what differs between subject groups in these experiments is that the deaf show less of a central visual field advantage than do hearing subjects [8,39,50]. In other words, peripheral vision in the deaf appears to be relatively enhanced. These perceptual findings have been supported by neural imaging results from VEP [51], fMRI [1], and MEG [21], which show selective enhancement of responses to peripheral, but not central, stimuli in deaf as compared to hearing subjects.

This peripheral visual field enhancement in the deaf has typically been attributed to one or both of two factors. First, it could be that, devoid of auditory cues to orient them to peripheral stimuli, deaf people must rely more heavily on peripheral vision than do hearing people (e.g., in the case of driving a car). Second, enhanced peripheral vision may arise due to experience with ASL. While conversing in ASL, signers unwaveringly fixate on each other's face in order to obtain pertinent inflectional and emotional information from facial expressions, and thus the motion of the hands is generally viewed peripherally. Recent work from our laboratory has shown that, at a viewing distance of 5 ft, ASL signs fall, on average, at an eccentricity of 7° (S.D.=± 2°) from fixation in the inferior visual field [9]. Both deaf and HOD subjects show enhancement of VEPs to peripheral vs. central stimuli over temporal and parietal areas of the left hemisphere, suggesting that these peripheral enhancements may indeed be due to ASL use [49]. However, in the present study, designed specifically to investigate differences between signers and non-signers in detection of stimuli moving at speeds ecologically relevant for ASL, we found no evidence for differences in central/peripheral contrast sensitivity ratios (C/P) across deaf, hearing and HOD subjects. Thus, enhanced performance for peripheral stimuli in deaf subjects does not appear to generalize to contrast sensitivity.

4.1.2. Right vs. left

In addition to previously-reported differences in central vs. peripheral processing, perceptual studies have also found a right (as compared to left) visual field advantage in deaf subjects when tested on a direction of motion task (whereas hearing subjects show an opposite trend) [7,8,50]. Based on the contralateral projections of the visual system, these results imply differential hemispheric advantages in deaf vs. hearing subjects, with a left hemisphere specialization for motion processing in the deaf. An enticing explanation for this motion asymmetry is based on an association between motion and language processing in deaf signers. That is, comprehension of American Sign Language is highly dependent on the ability to process moving hand signals, with the direction of hand motion often providing crucial linguistic information. Since evidence suggests that ASL is lateralized to the left hemisphere in deaf signers ([2,14,17,23,25,47,54,69] but cf. Ref. [48]), as is spoken language for hearing individuals, it has been suggested that motion processing may be 'captured' by the left, language-dominant hemisphere of the brain [5,50]. In support of this hypothesis, a right visual field/left hemisphere advantage for motion processing has also been observed for HOD subjects [7,8,49].

In the present study of contrast sensitivity, however, we found no evidence for a right visual field advantage in the deaf. These results are important for several reasons. First, they indicate that not all types of low-level vision are altered in deaf subjects. That is, while differences between groups are found on a motion task, they are not observed on a simple contrast sensitivity task. These differential results across tasks has implications for the neural level at which plasticity might occur in the deaf. Since contrast sensitivity is thought to be constrained by processes as early as the retinal ganglion cells of the eye [35], our null findings suggest no differences across subjects at this very early level of the system. In addition, even though our task was a detection and not a motion task, because our stimuli were moving gratings, these results show that the RVF advantage in the deaf for direction of motion discrimination is not due to increased sensitivity to moving stimuli, per se. Rather, these results suggest that the mechanisms underlying direction of motion discrimination and contrast detection of moving gratings are distinct and are separately affected by altered sensory experience. For example, directionally selective neurons in area V5/MT that underlie directional discrimination may be vulnerable to crossmodal plasticity affects, whereas neurons in the retina and V1 that subserve contrast sensitivity may not.

Second, if it is the case that only visual elements critical for ASL induce plasticity during development, our null finding for contrast sensitivity would suggest that this aspect of vision is not critical for ASL comprehension. This is perhaps not surprising since, under normal viewing conditions, the hands of the signer (with respect to the background) are well above contrast threshold, and thus the comprehension of ASL does not rely on the ability to detect near threshold stimuli (like those employed in the present experiment). In this context, right visual field/left hemisphere advantages in the deaf may be found only for those aspects of vision (such as direction of motion discrimination) that are crucial for language comprehension.

Finally, the lack of a right vs. left visual field asymmetry for contrast sensitivity tends to rule out the possibility that the previously observed visual field asymmetry for motion discrimination can be accounted for by biases in attention across the visual field. If such attentional biases could account for our previous findings on a motion discrimination task, visual field asymmetries would presumably be found on all tasks, including contrast detection. Although there is evidence that attentional processes may, in fact, be altered in the deaf under some conditions (see below), the present findings suggest a lack of attentional biases across the visual field in the deaf. These cumulative results suggest that left vs. right visual field asymmetries may be unique to direction of motion processing, and are most likely due to a lifetime of experience with ASL.

4.1.3. Superior vs. inferior

Our main motivation for investigating superior vs. inferior visual field asymmetries was based on the fact that most ASL signs fall in the viewer's inferior visual field, i.e., below the level of the signer's eyes (mean eccentricity=7±2°, [9]). We did not, however, find any differences in superior/inferior sensitivity ratios (S/I) across subject groups. As above, these null findings might be explained by a lack of inter-dependence between contrast sensitivity and ASL comprehension.

4.2. Conclusions

In conclusion, while differences between deaf and hearing subjects have been shown for many high-level, visual-cognitive tasks, differences on low-level tasks appear to be found only for selective aspects of visual perception. Specifically, previous studies assessing direction of motion discrimination have revealed differential visual field asymmetries between deaf and hearing subjects. However, the contrast sensitivity task of the present study, as well as other tasks such as brightness discrimination, temporal discrimination, and temporal resolution reveal no differences between groups. Since the ability to discriminate the direction of hand movements is important for ASL use, whereas performance on these other tasks is not, these cumulative results suggest that perhaps only those aspects of visual perception that are important for ASL comprehension may be affected in the deaf. Interestingly, recent studies demonstrating enhanced attentional abilities in deaf subjects [6,7,44,56,61,76] may also result from ASL experience, since conversing in ASL involves fixating on the signer's face while attending to the position and motion of the hands that fall in the periphery. Investigations in our laboratory are currently underway to determine whether these attentional effects are, in fact, due to ASL use as opposed to deafness per se.

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