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Hemispheric Asymmetries in Deaf and Hearing During Sustained Peripheral Selective Attention

O. Scott Gwinn^{1,2,*} and Fang Jiang¹

¹University of Nevada, Reno and ²College of Education, Psychology and Social Work, Flinders University, Adelaide, South Australia, Australia, 5042

*Correspondence should be sent to O. Scott Gwinn (e-mail: dr.scottgwinn@gmail.com)

Abstract

Previous studies have shown that compared to hearing individuals, early deaf individuals allocate relatively more attention to the periphery than central visual field. However, it is not clear whether these two groups also differ in their ability to selectively attend to specific peripheral locations. We examined deaf and hearing participants' selective attention using electroencephalography (EEG) and a frequency tagging paradigm, in which participants attended to one of two peripheral displays of moving dots that changed directions at different rates. Both participant groups showed similar amplifications and reductions in the EEG signal at the attended and unattended frequencies, indicating similar control over their peripheral attention for motion stimuli. However, for deaf participants these effects were larger in a right hemispheric region of interest (ROI), while for hearing participants these effects were larger in a left ROI. These results contribute to a growing body of evidence for a right hemispheric processing advantage in deaf populations when attending to motion.

Individuals experiencing early and persistent unisensory deprivation can show heightened sensitivity in the remaining intact senses. For example, early blind individuals can exhibit superior auditory processing abilities compared to sighted individuals (Röder et al., 1999), while early deaf individuals can exhibit superior processing abilities in some visual tasks (for a review, see Bavelier, Dye, & Hauser, 2006). Such changes in sensory processing have been attributed to the phenomenon of neural plasticity (Lomber, Meredith, & Kral, 2010; Rauschecker, 1995; for a review, see Bavelier & Neville, 2002). Neural plasticity describes the process whereby the nervous system modifies its organization, through normal maturation and learning, as well as after damage and sensory deprivation (Bavelier & Neville, 2002). In the case of deaf individuals, this has been observed as the primary auditory cortex responding to visual stimuli (Finney, Clementz, Hickok, & Dobkins, 2003; Finney, Fine, & Dobkins, 2001; Scott, Karns, Dow, Stevens, & Neville, 2014). The recruitment of areas deprived of their normal sensory input can increase the cognitive resources available to process signals from remaining intact senses and facilitate greater processing power (for a review, see Merabet & Pascual-Leone, 2010).

The enhancements in visual processing observed in early deaf individuals have typically been isolated to the processing of peripheral motion (Armstrong, Neville, Hillyard, & Mitchell, 2002). Enhancements in face processing have also been shown (Arnold & Murray, 1998; McCullough & Emmorey, 1997), although these appear to result from experience with sign language rather than a loss of hearing (Bettger, Emmorey, McCullough, & Bellugi, 1997; Parasnis, Samar, Bettger, & Sathe, 1996; Stoll et al., 2017). Behavioral studies have indicated that enhancements in the processing of peripheral stimuli seen in deaf individuals can be attributed to allocating a greater proportion of attentional resources to these locations compared to hearing individuals (Loke & Song, 1991; Proksch & Bavelier, 2002; Sladen, Tharpe, Ashmead, Grantham, & Chun, 2005; for a review, see Dye & Bavelier, 2010). This conclusion has also been supported by neuroimaging studies employing functional magnetic resonance imaging (fMRI) (Bavelier et al., 2000, 2001; Scott et al., 2014) and electroencephalography (EEG) (Neville & Lawson, 1987). Using an event-related potential (ERP) design, Neville and Lawson (1987) demonstrated that larger increases in response amplitudes were exhibited by deaf participants compared to hearing participants

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when attending to peripherally presented motion stimuli. These differences between groups were not seen for centrally presented stimuli (Neville & Lawson, 1987).

Previous studies showing that deaf individuals are more distracted by peripheral stimuli (Proksch & Bavelier, 2002) may indicate that the greater allocation of attention to the periphery in deaf populations is largely involuntary and nonlocalized. However, later studies have suggested that deaf populations also exhibit greater control over their selective visual attention in the periphery (Dye, Hauser, & Bavelier, 2009; Seymour et al., 2017; for failed replication, see Dye, 2016). The ability to selectively focus one's attention has been likened to an attentional "spotlight" (Norman, 1968; Posner, Snyder, & Davidson, 1980) or "zoom lens" (Eriksen & St. James, 1986) that can be engaged to select a particular stimulus or area of the visual field. To examine selective attention in deaf and hearing populations, Dye et al. (2009) used a modified version of the useful field of view task (UFOV; Ball, Beard, Roenker, Miller, & Griggs, 1988), in which participants perform a central discrimination task while concurrently performing a peripheral visual search task. They found that compared to hearing participants, deaf participants required the displays to be presented for significantly less time to correctly identify the location of peripheral targets, which was interpreted as an enhancement in selective attention in deaf populations. However, Seymour et al. (2017) have noted that the targets used by Dye et al. (2009) not only differed from the distractors in terms of shape but also luminance. In developing feature integration models of attention (Treisman & Gelade, 1980), studies have shown that luminance is a preattentive visual feature (Treisman & Gormican, 1988; Wolfe & Franzel, 1988), which questions whether results from the UFOV task truly reflect differences in selective attention. Seymour et al. (2017) used targets and distractors of equal luminance; however, targets were now defined by orientation, which is also a preattentive feature (Sagi & Julesz, 1984; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). As such it perhaps remains unclear whether deaf and hearing individuals do differ in their control over selective visual attention.

While the effects of selective attention are readily observable in behavioral paradigms, such as cueing tasks (Bashinski & Bacharach, 1980; Posner, 1980), they can also have a large effect on the response properties of neural populations (for reviews, see Hillyard & Anllo-Vento, 1998; Yantis & Serences, 2003). Frequency tagging paradigms, based on the steady state visual evoked potential (Regan, 1966), have proved particularly effective in studying attention and its effect on neural responses (Morgan, Hansen, & Hillyard, 1996). In these studies, two or more stimuli are repeatedly presented at different frequencies and observers are instructed to selectively attend to one of the stimuli. Responses are analyzed in the frequency domain and the amplitude of responses at the frequency of the attended stimulus is found to be greater than those at the unattended frequency (Belmonte, 1998; Ding, Sperling, & Srinivasan, 2005; Müller, Malinowski, Gruber, & Hillyard, 2003; Müller et al., 1998; Toffanin, de Jong, Johnson, & Martens, 2009). As a result, the relative amplitude of the response at the attended frequency provides an effective measure of the degree to which an observer is able to attend to one location or stimulus at the exclusion of others. Frequency tagging has many advantages, including the production of high signal-to-noise ratios (SNR) with relatively few participants that even allows for significant stimulus-driven responses to be observed at an individual level (Norcia, Appelbaum, Ales, Cottareau, & Rossion, 2015; Rossion, 2014a, 2014b).

In the current study we examined deaf and hearing participants' sustained peripheral selective attention. Previous studies examining these two groups' selective attention may have instead been comparing preattentive performance or at least the transient component of attention. Sustained attention is engaged by presenting a stable cue directing observers' attention to a certain location in the visual field, while transient attention is engaged by briefly flashing cues in target locations (Nakayama & Mackeben, 1989). While researchers continue to seek clarification regarding how clear the distinction is between sustained and transient attention, sustained attention is thought to operate at a later stage of visual processing and enhances processing of a selected region via contrast gain, whereas transient attention operates earlier and involves a combination of response and contrast gain (Ling & Carrasco, 2006; Nakayama & Mackeben, 1989). We examined deaf and hearing participants' sustained peripheral attention using a frequency tagging design in which two fields of dots presented at separate peripheral locations alternated between coherent and incoherent motion at different rates, with participants instructed to attend to one field while ignoring the other. Frequency tagging was identified as an appropriate method to address the aims of the study as it provides a more continual measure of attention compared to other approaches, such as cueing tasks or ERP designs, making it well suited to the study of sustained attention. Motion stimuli were used as it is during motion processing that advantages in deaf populations are most often observed (Bavelier et al., 2006). Following previous reports of deaf individuals exhibiting greater control over their peripheral selective visual attention (Dye et al., 2009; Seymour et al., 2017), we hypothesized that compared to hearing participants, deaf participants would show a greater difference in amplitudes between responses at the attended frequency compared to the unattended frequency.

Methods

Participants

As the first study to use EEG and frequency tagging to examine attention in deaf and hearing individuals, precise power analyses prior to determining an appropriate sample size were not possible. However, the high SNR afforded by frequency tagging has seen significant differences in blood oxygen level-dependent responses to dot motion stimuli between deaf and hearing individuals using 12 participants (i.e. six Hearing and six Deaf; Retter, Webster & Jiang, 2019). Using EEG and an ERP design, which is known to produce poorer SNRs than frequency tagging (Rossion, 2014a; Rossion et al., 2015), Neville and Lawson (1987) observed significant differences in response amplitudes between deaf and hearing individuals when attending to peripheral motion using 24 participants. With the current study combining design elements from Retter et al.'s (2019) and Neville and Lawson's (1987) experiments, we averaged the sample sizes used in each and adhered to a stopping rule of 18 participants. The nine hearing (four female) participants had a mean age 33.44 (SD = 7.14) and nine severe to profoundly deaf (seven female) participants had a mean age of 39.56 (SD = 11.66). An independent samples *t* test showed that the difference in ages between groups was not significant ($t_{16} = 1.34$, $p = .2$, $d = .63$). All participants were right-handed and optical corrections were worn if necessary. Deaf participants had no history of neurological disorders and had a binaural severe-profound hearing loss (greater than 80 dB in the better ear). All of the deaf participants were fluent in American Sign Language, and none of the hearing participants

were signers. All participants received monetary compensation for taking part in the study. The study was approved by the Institution Review Board of the University of Nevada, Reno and conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Stimuli

A video clip of one trial can be found in Supplementary Material. Two fields of drifting square dots were generated using Matlab 2013b (MathWorks, United States). Each field was confined to separate circular apertures that were 10° of visual angle in diameter. One aperture appeared 20° to the left of a central fixation cross, measured from the center of the fixation cross to the center of the aperture, while the other appeared 20° to the right. Individual dots were $.15^\circ \times .15^\circ$ in size and were arranged in a density of nine dots per degree of visual angle. On each frame the dots changed their spatial location by $.05^\circ$. When presented at a rate of 120 Hz this resulted in apparent motion of 6° per second. Each dot had a lifetime of 24 frames (200 ms), at which point it was replaced by the generation of a new dot at a random location within the aperture. During periods of coherent motion, all the dots within an aperture travelled in the same direction. During periods of noncoherent motion, individual dots travelled in random directions. Within an aperture the stimulus would alternate between periods of coherent and noncoherent motion at a rate of 1.72 Hz or 2 Hz. The two apertures always alternated at different rates, such that if the left aperture was alternating at 1.72 Hz, the right alternated at 2 Hz. Beginning with the dots moving upwards at 90° , they would shift clockwise by 90° at each change of direction. When alternating at a rate of 2 Hz, over the course of 2 s the stimulus would follow a direction pattern of 90° (up), random, 0° (right), random, 180° (down), random, 270° (left), random. When alternating at 1.72 Hz, this pattern occurred over 2.33 s. Once the sequence had gone through a full 360° rotation it would begin again. Sequences were saved as 240 individual images in the case of 2 Hz and 280 images in the case of 1.72 Hz. This design meant that when attending to the 1.72 Hz alternation, participants necessarily had more time in which to perceive the direction of motion before it changed. Stimuli were presented on a NEC AccuSync 120 cathode ray tube monitor, with a screen size of 450×350 mm, working resolution of 800×600 pixels and refresh rate of 120 Hz. Stimuli were viewed from a distance of approximately 35 cm.

Procedure

The experiment took place in a quiet, darkened room. The whole session for each participant lasted for approximately 1 hr, including 30 min of preparation and 30 min of recording. Images were presented using custom software running over Java 8 (Oracle, United States). A single trial consisted of a 1 min sequence in which stimuli alternated between coherent and noncoherent motion by means of a square wave modulation at a 100% duty cycle. During each trial, participants were required to fixate on a small cross in the center of the screen while attending to one of the apertures in their periphery and ignoring the other. To help maintain attention on one of the apertures and fixation in the center, 6 times during a trial the fixation cross would briefly change to a square at random intervals, and at that time participants were required to indicate in which direction the dots were traveling in the aperture being attended to. Responses were provided by initiating a key press. Due to software limitations

and the dependent measure being neural response amplitudes rather than behavioral accuracy, key presses were not recorded. The experiment was divided into four blocks defined by the condition being run in that block. Conditions in the experiment were defined by the aperture being attended to and the alternation frequency in that aperture. This resulted in the four conditions: (a) attend left 1.72 Hz, (b) attend left 2 Hz, (c) attend right 1.72 Hz, and (d) attend right 2 Hz. Six repeated trials were run for each condition. The order of conditions was randomized across participants.

EEG Acquisition

The data were recorded using a BioSemi ActiveTwo system with a 128 Ag-AgCl Active-electrode array (BioSemi B.V., Amsterdam, Netherlands; for exact position coordinates, see <http://www.biosemi.com/headcap.htm>; for a conversion of these coordinates to a more standard 10–5 nomenclature (Oostenveld & Praamstra, 2001), see Rossion, Jacques, & Liu-shuang, 2015). Electrode offsets were kept below 30 mV, referenced to the common mode sense and driven right leg loop. Four additional electrodes were used to record vertical and horizontal electrooculogram (EOG): two electrodes were placed above and below participants' right eye and two were placed lateral to the external canthi. The EEG and EOG were digitized at a sampling rate of 2,048 Hz and then downsampled to 512 Hz.

Analysis

The recorded EEG was analyzed using Letswave 5, an open source toolbox (<https://www.letswave.org/>), running over MATLAB R2013b (MathWorks, United States).

Preprocessing. Data files for each participant were first filtered using a fourth order zero-phase Butterworth band-pass filter, with cut-off values of .1–120 Hz. A Fast Fourier Transform (FFT) multi-notch filter with a width of .5 Hz was also applied to remove electrical noise at three harmonics of 60 Hz. The data were then segmented by trial, including 1 s before and after the beginning of stimulation. To correct for artifacts caused by eye blinks, independent component analysis with a square matrix was applied (Hyvarinen & Oja, 2000). A single component was removed for four hearing participants and two deaf participants who blinked more than .2 times/s on average during the 60 s stimulation sequences. This cut-off is similar to that used in previous studies (e.g. Retter & Rossion, 2016b). Corrections were not made for lateral eye movements; however, these were inspected as a means of determining whether participants maintained central fixation during the experiment. Using Lins, Picton, Berg and Scherg's (1993) standard of a 10° horizontal saccade equating to a deflection of 164 μ V between electrodes placed at the external canthi, we compared the number of times per 1 min trial that deaf and hearing participants made a saccade from the central fixation cross to the inner most edge of the target aperture. The number of saccades made per trial by hearing participants ($M = .5$, $SD = .72$) was not significantly different to the number made by deaf participants ($M = .58$, $SD = .54$) ($t_{14} = .25$, $p = .810$, $d = .12$). Channels containing artifacts across multiple trials were replaced with the average of three to four neighboring channels. This was performed for a maximum of four channels per participant. All channels were then re-referenced to the common average. For each participant, trials were re-segmented

Figure 1 Scalp topographies for deaf and hearing participants showing responses at 1.72 Hz and 2 Hz in the four conditions (“VF” refers to visual field). Note that the two rows are split by attended versus unattended, meaning that topographies in the first two columns of the top row are showing responses at 1.72 Hz, while in the second two columns they are showing responses at 2 Hz.

to exclude the additional 1 s at the beginning and end of the sequences. Trials were then averaged within each condition.

Frequency domain analysis. An FFT was computed for each participant, condition, and channel, transforming the EEG data into separate frequency-domain amplitude spectra. Recordings were analyzed using a whole scalp analysis as well as left and right regions of interest (ROI). Left and right ROIs were broadly defined to include the average of all electrodes to the left or right of the midline, resulting in each ROI comprising 55 channels.¹ When displaying the amplitude spectra and comparing differences in amplitude, baseline corrections were applied to account for differences in baseline noise across participants and across the frequency spectrum within participants. This took the form of a baseline subtraction in which the average of the 20 surrounding bins, excluding the immediately adjacent bins and the local maximum and minimum amplitude bins, was subtracted from the bin of interest ($x' = x - \text{baseline}$). When comparing differences in amplitude, the sum of baseline-subtracted harmonics of the frequency of interest was also computed (Retter & Rosion, 2016a; see also Heinrich, 2009). The number of harmonics summed was determined by the condition with highest continuation of significant harmonics.

Results

Whole Scalp

Scalp topographies for responses at the attended and unattended frequencies can be seen in Figure 1. Full amplitude spectra are included in Figure S1 in Supplementary Material, and individual scalp topographies in Figure S2. Continuously significant responses at attended frequencies were observed up to the 6th harmonic in one condition in the hearing group. Baseline subtracted amplitudes were summed up to the 6th harmonic (12 Hz for the 2 Hz alternation rate and 10.32 Hz for the 1.72 Hz rate) for each condition and participant. Preliminary analyses showed that despite participants having more time to perceive the direction of motion when attending to the 1.72 Hz alternation, the amplitude of responses when attending to the two alternation frequencies were not significantly different ($t_{17} = 1$, $p = .333$, $d = .2$), which suggests neither frequency

could be attended to with greater ease. Data were averaged across these conditions prior to further analyses. Data were analyzed using a $2 \times 2 \times 2$ mixed measures analysis of variance (ANOVA), with the within-participants factors of Attend (whether the bin frequency corresponded to the attended vs. unattended motion alternation frequency), Field (the visual field being attended to, left vs. right), and the between-participants factor of Group (hearing vs. deaf). A significant main effect of Attend was found ($F_{1,16} = 29.46$, $p < .0001$, $\eta_p^2 = .65$), with amplitudes larger at the attended frequency ($M = .16$, $SD = .08$) compared to the unattended frequency ($M = .07$, $SD = .05$). No significant effects of Field ($F_{1,16} = .21$, $p = .65$, $\eta_p^2 = .01$) or Group ($F_{1,16} = .02$, $p = .905$, $\eta_p^2 = 0$) were observed. The Attend*Group interaction was nonsignificant ($F_{1,16} = .95$, $p = .345$, $\eta_p^2 = .06$), indicating deaf and hearing groups were able to selectively attend to the relevant motion displays to the same degree. All other interactions were also nonsignificant (all $p > .05$).

Left and Right ROIs

Significant responses at attended frequencies were observed up to the 6th harmonic in one condition in the hearing group. Baseline subtracted amplitudes were summed up to the 6th harmonic for each ROI, condition, and participant. Data were analyzed using a $2 \times 2 \times 2 \times 2$ mixed measures ANOVA with the within-participants factors ROI (the region from which the data came, left vs. right), Attend, Field, and the between-participants factor of Group. A significant main effect of Attend was again found ($F_{1,16} = 26.62$, $p < .001$, $\eta_p^2 = .63$), with amplitudes larger at the attended frequency ($M = .16$, $SD = .08$) than the unattended frequency ($M = .07$, $SD = .05$). Other main effects of ROI ($F_{1,16} = .19$, $p = .671$, $\eta_p^2 = .01$), Field ($F_{1,16} = .81$, $p = .382$, $\eta_p^2 = .05$), and Group ($F_{1,16} = .01$, $p = .934$, $\eta_p^2 = 0$), were nonsignificant.

A significant three-way ROI*Attend*Group interaction was found ($F_{1,16} = 7.47$, $p = .015$, $\eta_p^2 = .32$). In Figure 2 it can be seen that the difference between amplitudes at the attended frequency compared to the unattended frequency appears larger in the left ROI than the right ROI for hearing participants, whereas for deaf participants the difference appears larger in the right ROI than the left ROI. A total of 4 one-sample t tests were used to first determine whether the effect of attention was significant in both ROIs for both participant groups. Using a Bonferroni correction,

Figure 2 Mean difference between baseline subtracted amplitudes at the attended frequency compared to the unattended frequency, summed across the first six harmonics, in the left and right ROIs for deaf and hearing participants. For deaf participants, the larger mean for the dark blue bar indicates a greater effect of attention on response amplitudes in the right ROI. Conversely, for hearing participants the larger mean for the light blue bar indicates the effect is relatively greater in the left ROI. Data for individual participants are represented by colored shapes. Error bars show standard error of the mean.

the critical alpha for these tests was set at $\alpha = .0125$. For deaf participants, the difference between amplitudes at the attended frequency compared to the unattended frequency was significant in both the right ROI ($M = .09$, $SD = .07$) ($t_8 = 4.12$, $p = .003$, $d = 1.52$) and the left ROI ($M = .06$, $SD = .06$) ($t_8 = 3.24$, $p = .012$, $d = 1.21$), but with a smaller effect size in the left. For hearing participants the opposite was found, with a significant difference in the left ROI ($M = .12$, $SD = .09$) ($t_8 = 4.28$, $p = .003$, $d = 1.42$) and in the right ($M = .09$, $SD = .08$) ($t_8 = 3.39$, $p = .010$, $d = 1.22$), but with a smaller effect in the right. Two additional paired-samples t tests were used to explore these differences in effect size between ROIs for the two participant groups. Using a Bonferroni correction, the critical alpha for these comparisons was set at $\alpha = .025$. For hearing participants, the difference between amplitudes at the attended frequency compared to the unattended frequency was not significantly different between the left ROI and the right ROI ($t_8 = 1.57$, $p = .156$, $d = .37$). In contrast, for deaf participants, the difference between amplitudes at the attended frequency compared to the unattended frequency was significantly greater in the right ROI compared to the left ROI ($t_8 = 3.39$, $p = .009$, $d = .51$).

In Figure 2 it appears as though the observed three-way interaction may also be attributable to a potentially significant difference between the two participant groups in the left ROI but not in the right ROI. This was examined using two independent-samples t tests. Using a Bonferroni correction, the critical alpha for these comparisons was set at $\alpha = .025$. The difference between amplitudes at the attended frequency compared to the unattended frequency was not significantly different between the two participant groups in both the left ROI ($t_{16} = 1.77$, $p = .095$, $d = .84$) and the right ROI ($t_{16} = .13$, $p = .901$, $d = .06$). This indicates the interaction can be attributed to the previously identified significantly larger mean difference in the right ROI compared to the left ROI for deaf participants and the relatively larger mean difference in left ROI compared to the right ROI for hearing participants.

A significant three-way ROI*Field*Attend interaction was also found ($F_{1,16} = 38.83$, $p < .001$, $\eta_p^2 = .67$), indicating that the difference between amplitudes at the attended frequency compared to the unattended frequency is largest in the ROI contralateral to the field being attended to. While the current task likely involves attentional systems beyond initial low-

level visual processing, this result is perhaps to be expected given the anatomy of the human visual system and the optic nerves crossing at the optic chiasma and as such will not be considered further. All other interactions were nonsignificant (all $p > .05$).

Discussion

We used EEG and a frequency tagging paradigm to examine deaf and hearing participants' control over their sustained peripheral visual attention. Fields of moving dots that changed directions at different frequencies were presented in the left and right periphery, and participants were instructed to attend to one field while ignoring the other. Larger response amplitudes were observed at the attended frequencies than at the unattended frequencies. The magnitude of this effect was not significantly different between the deaf and hearing participants. However, deaf participants showed significantly greater effects of attention in a right hemisphere ROI compared to a left ROI, while hearing participants showed a relatively greater effect in the ROI than the right ROI.

Previous behavioral and neuroimaging studies have shown that compared to hearing controls, deaf individuals naturally allocate more attentional resources to the periphery (Bavelier et al., 2000, 2001; Neville & Lawson, 1987; Proksch & Bavelier, 2002; Scott et al., 2014; Sladen et al., 2005) and are also able to localize peripheral targets more efficiently (Dye et al., 2009; Seymour et al., 2017). The current study represents the first investigation into deaf and hearing individuals' ability to selectively attend to and sustain processing of competing peripheral stimuli. While somewhat exploratory, we hypothesized that deaf participants would show a greater ability to selectively attend to specific peripheral locations. However, the results showed that differences in amplitude at the attended and unattended frequencies were similar across the two groups. Modulation of frequency tagged amplitudes is a well-established paradigm for studying visual attention (Belmonte, 1998; Ding et al., 2005; Morgan et al., 1996; Müller et al., 1998, 2003), and these effects have further been shown to be sensitive to gradations in attention, rather than reflecting a simple attended versus unattended dichotomy (Toffanin et al., 2009). As such, relative modulations of amplitudes provide an effective measure of attentional control. The similar effects across groups indicates that both deaf and hearing participants exhibit similar control over their selective peripheral visual attention for motion stimuli when required to sustain processing over extended periods.

The current results indicate that previous reports of enhanced selective attention in deaf populations (Dye et al., 2009; Seymour et al., 2017) do not extend to tasks requiring sustained attention. This may be because previous tasks were engaging preattentive processing or a more transient form of attention. Transient attention is thought to follow a "bottom-up" stream of processing, being more stimulus driven and automatic. Conversely, sustained attention is thought to be more "top-down" and under conscious control (Ling & Carrasco, 2006; Nakayama & Mackeben, 1989). Several studies have shown that auditory areas of deaf individuals can be recruited during the exercise of executive functions under conscious control, such as linguistic processing (Cardin et al., 2013) and working memory tasks (Bavelier et al., 2008; Buchsbaum et al., 2005; Cardin et al., 2017; Ding et al., 2015). However, this cortical reorganization is not associated with enhancements in processing, with

deaf and hearing individuals performing these tasks with similar accuracy (Bavelier et al., 2008; Cardin et al., 2017; Ding et al., 2015).

While speculative, the present findings may indicate that the redistribution of attention to the periphery observed in deaf populations serves a more general monitoring role, designed to detect changes in the environment rather than promote sustained detailed processing. This position is perhaps supported by behavioral studies showing that processing advantages in deaf populations are only observed for specific tasks and stimulus types. That is, deaf participants have been shown to be faster at reacting to the presentation of peripheral stimuli compared to hearing participants (Loke & Song, 1991; Stevens & Neville, 2006) and are also able to switch between task irrelevant and relevant peripheral locations more quickly (Colmenero, Catena, Fuentes, & Ramos, 2004; Parasnis & Samar, 1985). In contrast, deaf and hearing participants have been shown to perform equally in tasks requiring more fine-grain discrimination of motion direction in the periphery (Bosworth & Dobkins, 1999, 2002). Although, experienced signers have been shown to fixate the mouth and chin area during a conversation, using peripheral vision to process hand gestures (Agrafiotis, Canagarajah, Bull, & Dye, 2003), and Deaf signers can show processing advantages when tasks occur in the inferior visual field (Bosworth & Dobkins, 2002; Dye, Seymour, & Hauser, 2016). It is therefore possible that they may also show sustained attention advantages for stimuli presented within this area. Such an investigation may prove an interesting avenue for future research.

While deaf and hearing participants both showed equal attentional effects on the amplitudes of the tagged frequencies, the two groups differed in the extent to which these effects were observed in the left versus right ROIs. A significant three-way interaction showed a relatively larger effect of attention in left ROI compared to the right ROI for hearing participants, which contrasted with a larger effect in the right ROI compared to the left ROI for deaf participants. For deaf participants, the difference between ROIs was significant. It is worth noting that this effect occurred in the absence of any additional interactions involving the visual field being attended to. That is, the greater effect of attention observed in the right ROI for the deaf group was not simply because they were attending more to the left visual field. The laterality asymmetry observed in the present study is similar to the greater activation of the right hemisphere in deaf participants during motion processing tasks reported in previous studies using fMRI (Fine, Finney, Boynton, & Dobkins, 2005; Finney et al., 2001), functional near-infrared spectroscopy (Dewey & Hartley, 2015), magnetoencephalography (Finney et al., 2003), and EEG (Sandmann et al., 2012). Greater thickness of the right auditory cortex (planum temporale) has also been shown to correlate with better visual motion detection in deaf populations (Shiell, Champoux, & Zatorre, 2016). To our knowledge, only one fMRI study (Bavelier et al., 2001) and one EEG study (Neville & Lawson, 1987) have found evidence of a left hemispheric advantage in Deaf. The current results contribute to the growing body of evidence for a right hemispheric advantage in deaf populations.

Behavioral investigations of motion processing in deaf and hearing populations have also found evidence of visual field asymmetries between the two groups. These studies typically show a right visual field processing advantage in Deaf (Bosworth & Dobkins, 1999, 2002; Bosworth, Petrich, & Dobkins, 2013; Brozinsky & Bavelier, 2004; Neville & Lawson, 1987; for left field advantage, see Hauthal, Sandmann, Debener, & Thorne,

2013). Within these studies many have assumed this right field behavioral advantage would naturally be associated with a contralateral left hemisphere advantage. However, from the present results and those from the studies discussed above, this does not appear to be true. Retter et al. (2019) have suggested that this ipsilateral right visual field/right hemispheric advantage in deaf populations can be reconciled by the recruitment of remapped auditory cortices, which unlike other motion processing areas, such as middle temporal (MT), do not show strong contralateral biases, resulting in a right hemisphere dominance regardless of visual field. Of course, greater overall activity in one hemisphere does not necessarily indicate a processing advantage, as this may simply reflect compensatory systems working to rectify a deficit rather than enhancing processing above a base level. Indeed, Retter et al. (2019) found that while larger direction-selective (scrambled vs. coherent motion) responses to visual motion were observed in the auditory cortices of deaf participants, direction-specific (left vs. right) responses were similar across groups. While the limited spatial resolution of EEG means we cannot make definitive conclusions regarding the source of neurological activity, the relatively greater effect of attention on direction-selective responses in the right ROI for deaf participants compared to hearing participants observed in the current study may have similarly been supported by the involvement of auditory cortices. Behavioral accuracy was not assessed for the present selective attention task and future studies may wish to examine whether the right hemisphere dominance in deaf individuals for attention-modulated frequency-locked response is associated with an ipsilateral right visual field processing advantage.

Conclusion

Deaf and hearing individuals show similar control over selective attention in tasks requiring sustained processing of competing peripheral motion stimuli. These results raise the possibility that the redistribution of attention to the periphery observed in deaf populations serves a general monitoring role, designed to detect changes in the environment rather than promote sustained processing. Deaf individuals also show a right hemisphere processing advantage when selectively attending to peripheral motion, perhaps reflecting the processing of visual information in areas typically sensitive to auditory input.

Supplementary Data

Supplementary data is available at *Journal of Deaf Studies and Deaf Education* online.

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Conflicts of Interest

No conflicts of interest were reported.

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Notes

¹ In other analyses not reported here, ROIs were defined using a data-driven method similar to Toffanin et al. (2009), resulting in 17 occipito-parietal electrodes comprising the right ROI and 13 electrodes comprising the left ROI. Defining ROIs in this way does not alter the outcomes of the study.

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