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Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test

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Abstract

The loss of one sensory modality can lead to a reorganization of the other intact sensory modalities. In the case of individuals who are born profoundly deaf, there is growing evidence of changes in visual functions. Specifically, deaf individuals demonstrate enhanced visual processing in the periphery, and in particular enhanced peripheral visual attention. To further characterize those aspects of visual attention that may be modified by deafness, deaf and hearing individuals were compared on the Attentional Network Test (ANT). The ANT was selected as it provides a measure of the efficiency of three neurally distinct subsystems of visual attention: alerting, orienting and executive control. The alerting measure refers to the efficiency with which a temporal cue is used to direct attention towards a target event, and the orienting measure is an indicator of the efficiency with which a spatial cue focuses attention upon that target's spatial location. The executive control measure, on the other hand, is an indicator of the amount of interference from peripheral flankers on processing that central target. In two separate experiments, deaf and hearing individuals displayed similar alerting and orienting abilities indicating comparable attention across populations. As predicted by enhanced peripheral attention, deaf subjects were found to have larger flanker interference effects than hearing subjects. These results indicate that not all aspects of visual attention are modified by early deafness, suggesting rather specific effects of cross-modal plasticity.

Keywords: Attention; Deafness; Peripheral vision; Flanker; Orienting; Attentional Network Test

1. Introduction

Sensory deprivation, such as blindness or deafness, can lead to changes in the processing of information from the remaining sensory modalities (see Bäckman & Dixon, 1992; Bavelier & Neville, 2002; Sur, 2004 for reviews). This fact is now well documented in the animal (Rauschecker & Kniepert, 1994) as well as the human literature with blind (Amedi, Raz, Pianka, Malach, & Zohary, 2003; Cohen et al., 1997; Roder, Stock, Bien, Neville, & Rosler, 2002; Weeks et al., 2000) and deaf individuals (Bavelier et al., 2001; Fine, Finney, Boynton, & Dobkins, 2005; Finney, Fine, & Dobkins, 2001; Lambertz, Gizewski, de Greiff, & Forsting, 2005; Levänen & Hamdorf, 2001; Sadato et al., 2005). In the case of deafness, a number of studies suggest altered visual skills. Interestingly, a review of this literature indicates a rather high level of functional specificity in the changes observed, as changes have been reported in peripheral visual processing (Neville & Lawson, 1987a, 1987b; Stevens & Neville, 2006), but no changes in psychophysical thresholds have been observed (Bosworth & Dobkins, 1999; Bross, 1979; Bross & Sauerwein, 1980; Brozinsky & Bavelier, 2004; Finney & Dobkins, 2001). The aim of our study is to investigate further which aspects of visual processing may be modified by early deafness.

1.1. Peripheral attention

A review of the existing literature on those aspects of visual processing that may differ between deaf and hearing individuals indicates clear differences in peripheral attention between populations (Loke & Song, 1991; Neville & Lawson, 1987a, 1987b; Stevens & Neville, 2006). For example, Loke and Song (1991) presented subjects with a target detection task either at central (0.5°) or peripheral (25°) locations. All subjects were faster to respond to central targets than to peripheral targets, but more importantly, there was an interaction between deaf-

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ness and target location. While deaf and hearing subjects did not differ in their reaction times to central targets, deaf subjects were significantly faster than hearing subjects at responding to peripheral targets. More recently, Proksch and Bavelier (2002) used a flanker interference paradigm to characterize the spatial distribution of attentional resources in deaf and hearing individuals. In accordance with the view of greater peripheral attention in the deaf, peripheral flankers were more distracting in deaf than hearing individuals. In this design, target shapes were presented along an imaginary ring in para-foveal vision, and irrelevant flankers accompanied these shapes either centrally (inside the ring) or peripherally (outside of the ring), with those flankers being either response congruent (matching the target) or response incongruent (matching the non-target). Following the logic of Lavie and collaborators (Lavie, 2005), the size of a flanker interference effect was used as a measure of the attentional resources allocated to the distractor. The flanker interference effect was computed as the difference in performance between when a response incongruent distractor and when a response congruent distractor flanked the target. The proposal of enhanced peripheral attention in deaf individuals led to the hypothesis of a greater flanker interference effect from peripheral distractors in deaf than in hearing individuals—this prediction was borne out. Additionally, central distractors led, if anything, to greater flanker interference effects in the hearing as compared to deaf individuals, establishing that it is not the case that deaf individuals are overall more distractible. Rather, this pattern of results is consistent with the proposal that by default deaf individuals distribute their attention peripherally, whereas hearing individuals tend to focus their attention centrally. A recent paper by Sladen, Tharpe, Ashmead, Grantham, and Chun (2005) examined the effects of flanker interference in deaf and hearing subjects, varying the spacing of distractors to examine whether flankers had greater effects on deaf subjects when presented at peripheral locations. Here the target was a central arrow pointing to either the left or the right. Distractors were arrows flanking the target to the left and right, pointing in the same direction (congruent) or in the opposite direction (incongruent). Again, a flanker interference effect was computed as the difference in performance between incongruent and congruent flanker trials. In accordance with the view that peripheral attention is enhanced in deaf individuals, they observed a larger flanker interference effect for deaf subjects with flankers positioned at 1.0° and 2.0° from the target as compared to flankers positioned at 0.05° and 0.10°. However, deaf and hearing participants exhibited comparable interference effects with flankers positioned at 3.0° and 6.0°, suggesting a peak population difference around 1.0–2.0° away from the target. Neural markers of this peripheral enhancement have also been described. Neville and Lawson (1987a, 1987b), in an ERP study, presented deaf and hearing adults with a Posner-style cueing task, in which subjects were required to indicate the direction of apparent movement of targets presented centrally or peripherally in the context of distractors. They report that deaf subjects were faster and more accurate than hearing subjects at detecting the direction of movement in the periphery, but not centrally, and exhibited greater brain responses as indexed by the early negativity – N1 – to peripheral stimuli, but not central stimuli. In fMRI studies, Bavelier, Tomann et al. (2000); Bavelier et al. (2001)reported enhanced MT/MST recruitment and more effective connectivity between MT/MST and posterior parietal cortex in deaf signers when a task required them to direct their attention peripherally. A number of studies have shown that this peripheral enhancement is observed in deaf signers but not in hearing signers, establishing that signing in itself does not bring about this peripheral enhancement; rather deafness appears to be a driving factor (Bavelier et al., 2001; Neville & Lawson, 1987a, 1987b; Proksch & Bavelier, 2002; also see Fine et al., 2005 for a similar trend).

1.2. *Visual search*

There is therefore good agreement about enhanced peripheral visual attention after early deafness. Whether other aspects of visual attention may be modified as a result of early deafness seems more controversial. For example, a number of studies have compared deaf and hearing individuals on a visual search task. Stivalet, Moreno, Richard, Barraud, and Raphel (1998) concluded that deafness resulted in a shift from serial (attentive) to parallel (preattentive) processing. However, this conclusion, drawn upon the finding of a weak interaction between hearing status and set size, may mask other possible interpretations. Specifically, the most extensive study of visual search in deaf subjects to date reported that deaf subjects display an advantage over hearing controls but only in target-absent conditions (Rettenbach, Diller, & Sireteanu, 1999). Although this may indicate a more efficient serial search in the deaf population, it may alternatively reflect a decision bias in the deaf population leading those individuals to terminate their search more rapidly in the absence of a target. Such changes in decision bias have been reported in studies of visual searches in elderly subjects, where older observers take longer than younger individuals to terminate a search in target-absent trials (Hommel, Li, & Li, 2004). Finally, in a study by Bosworth and Dobkins (2002), the lack of a set size by population interaction, suggested that deaf and hearing subjects did not differ in how efficiently they could search for a target among distractors. Thus, the available evidence does not allow one to conclusively conclude that visual search is really more efficient after early deafness, but rather calls for more detailed studies of this aspect of attention.

1.3. *Spatial orienting*

Orienting, or the spatial relocation of attention, has also been measured as a function of hearing status. Several studies have used modifications of the Posner cueing paradigm (Posner, 1980) to examine the ability of deaf participants to orient their attention. Work by several authors indicates comparable benefits from a valid cue across deaf and hearing populations (Darves, Rueda, Stevens, Marrocco, & Neville, 2003; Parasnis, 1992; Parasnis & Samar, 1985). Population differences have been noted in only two studies. Bosworth and Dobkins (2002) observed that deaf individuals did not benefit as much from a valid cue as hearing individuals. This population difference was only present at the longest cue-target stimulus onset asynchrony (SOA) of 600 ms, and not at the shortest SOA of 200 ms, rendering the interpretation of this effect difficult. In a study by Parasnis and Samar (1985), deaf subjects were better at disengaging attention from an invalidly cued para-foveal location in the presence of irrelevant foveal information than were hearing subjects. The presence of competing central and peripheral demands in this paradigm may have helped in revealing a population difference, as deaf and hearing individuals appear to have different spatial distributions of attention.

This review of the literature indicates quite specific changes in visual attention in deaf individuals. It is not simply the case that deaf individuals clearly outperform hearing individuals on all aspects of visual attention. Rather, deafness appears to have differential effects on the different aspects of attention. Our aim is to further characterize those aspects of visual attention that may be altered following deafness. To this end, we have used the Attentional Network Test (ANT), which has been hypothesized to test three relatively separate subsystems of visual attention—alerting, orienting and executive control. In the ANT, subjects have to decide whether an arrow flanked by two distracting arrows is pointing left or right. On any trial, the set of arrows can be presented above or below the fixation point. Before the presentation of the arrows, a cue may be used to direct the attention of the participants. Three different types of cue are used, as well as a no-cue condition. Alerting is defined as the ability to make use of a temporally informative cue and is evaluated by comparing the no-cue condition to a double cue condition (a cue above and below fixation at the two possible target locations). Orienting is the ability to make use of a spatially informative cue above and beyond a temporally informative cue. Orienting is evaluated by comparing a center cue condition (where the cue is presented at fixation) to a single spatially informative cue that appears where the target arrow will appear. Finally, executive control (the ability to ignore incongruent distractors) has been evaluated by comparing trials in which the distractor arrows are incongruent with the target arrow to those where the distractor arrows are congruent; a measure of flanker interference similar to that of Proksch and Bavelier (2002) and Sladen et al. (2005).

These three different measures have been proposed to characterize three main components of attention (Fan, McCandliss, Sommer, Raz, & Posner, 2002) related to three attentional networks subserved by distinct neuroanatomical regions and modulated by specific neurotransmitters. Alerting is linked with right frontal and parietal areas, activated by release of noradrenalin; orienting is subserved by circuits in the parietal and frontal lobes and associated with release of acetylcholine; and executive control is seen as supported by areas in the prefrontal and cingulate cortex (Posner & Fan, in press), activated by release of dopamine. Supporting the view that these three aspects of attention are distinct, measures of alerting, orienting and executive control were found to be independent in that they did not significantly correlate with each other (Fan et al., 2002; Rueda et al., 2004; but see Callejas, Lupiáñez, & Tudela, 2004; Callejas, Lupiáñez, Funes, & Tudela, 2005 for discussions of possible interactions). In addition, Fan et al. (2002) reported that the ANT has high test–retest reliability in a sample of hearing adults. Thus the ANT seems to be a sensitive measure of three distinct aspects of visual attention. Our aim was to investigate whether the three networks identified by the ANT – alerting, orienting and executive control – may be changed as a result of early sensory (auditory) deprivation.

2. Experiment 1

To assess the impact of deafness upon alerting, orienting and executive control networks, we administered the ANT to a group of profoundly deaf college students who had deaf parents and acquired ASL as a first language. Their performance was compared to a control group of hearing college students, all of whom were native English speakers with no history of hearing loss, and no knowledge of any signed language.

2.1. Method

2.1.1. Subjects

Forty subjects participated in the study. Subjects who reported playing any action video games in the previous 12 months (two deaf males, one deaf female and two hearing males, two hearing females) were excluded from analyses as playing such games has been reported to influence visual attention skills (Green & Bavelier, 2003, 2006). Of the 33 remaining subjects included in the analyses, 17 were deaf signers aged 18–26 years ($M = 22$, $SD = 2$, 4 males) all of whom were born profoundly deaf to deaf parents. All deaf subjects had been exposed to and acquired ASL as a first language from birth, and had a 90 dB or greater loss in their better ear. Sixteen subjects had normal hearing, and were 19–27 years of age ($M = 22$, $SD = 2$, 3 males). All spoke only English and reported no exposure to ASL.

All subjects had normal or corrected-to-normal vision, no reported history of neurological impairment, and were right-handed. They were naïve to the aims of the study and paid for their participation. All subjects gave written informed consent and the protocols were given ethical approval by the University of Rochester Research Subjects Review Board and the Gallaudet University Institutional Review Board.

2.1.2. Apparatus and materials

Stimuli were presented on a 15-in. LCD display (DELL Computer Corporation) with a 1,024 × 768 pixel resolution and a 60 Hz frame rate. A Java script was used to run the experiment (available from http://sacklerinstitute.org/cornell/people/jin.fan/) under Mac OS X on a PowerBook G4 laptop. As a result the experimental details closely mirror those reported in Fan et al. (2002).

2.1.3. Stimuli and design

The experiment included one between subjects factor (*deafness*—deaf or hearing) and two within subjects factors (*flanker congruency*—incongruent, congruent, neutral; and *cue type*—none, center, double, spatial).

2.1.3.1. Flanker congruency. Flankers were two arrows presented horizontally aligned on either side of a central target arrow (see Fig. 1). Flankers could either be *incongruent* with the target (arrows pointing in the opposite direction), *congruent* with the target (arrows pointing in the same direction) or *neutral* (lines without arrowheads). Each arrow subtended 1.0° of visual angle, with the edges of adjacent arrows separated by 0.1° of visual angle. As a result, the arrow centers were spaced 1.55° apart. The arrows were presented 1.5° of visual angle above or below a central fixation point. The arrows appeared above or below the fixation point with equal probability.

2.1.3.2. Cue type. The *cue* consisted of one or two asterisks presently briefly prior to the onset of the arrow(s). The cue was either *absent*, *central* (presented at the fixation point), *double* (two cues presented simultaneously above and below the fixation point at both possible target locations) or *spatial* (a single cue

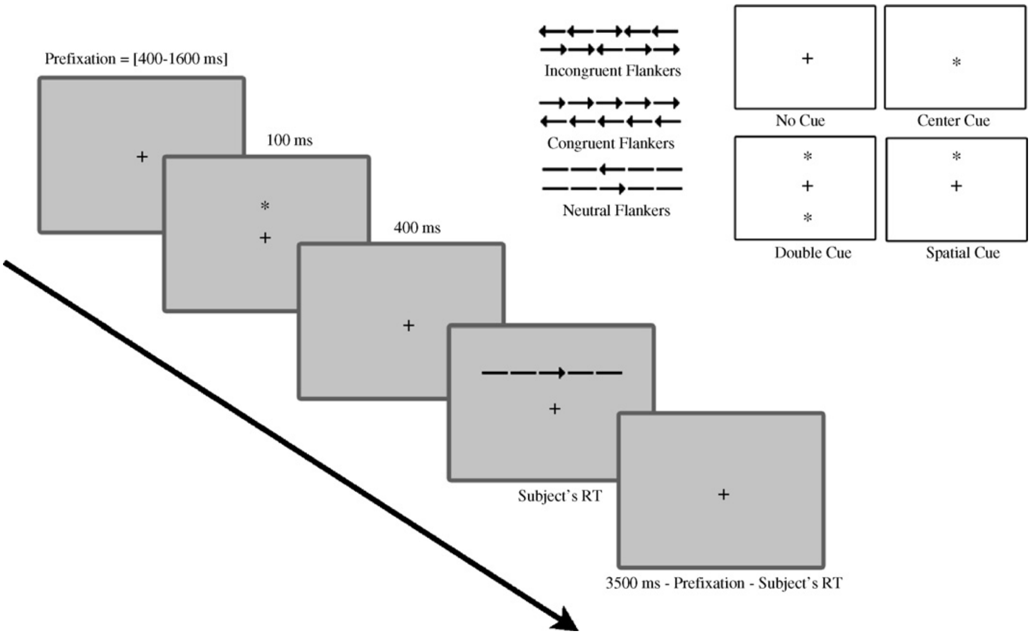

Fig. 1. A schematic diagram of the stimuli and design of Experiment 1.

presented above or below the fixation point and indicating the location of the subsequent target).

2.1.3.3. Trial structure. There were a total of 96 experimental trials for each subject in each block, determined by the combinations of flanker congruency (3), cue type (4), target location (2) and target direction (2), each presented twice within a block. Each subject participated in two blocks of experimental trials, with the first block preceded by 24 practice trials, resulting in a total of 216 trials overall.

The total duration of each trial was set to 4,000 ms. A pre-stimulus fixation point appeared for a variable duration of 400–1,600 ms. This was then accompanied by a cue presented for 100 ms. After the offset of the cue, there was a 400 ms interval prior to the onset of the arrow(s). The fixation point was present at all times. Following the subject's response, the arrows were removed from the display, leaving only the post-stimulus fixation point. The next trial was initiated after 3,500 ms minus the duration of the pre-stimulus fixation point and minus the reaction time of the subject (total duration = pre-stimulus fixation point + 100 + 400 + reaction time + 3,500 − pre-stimulus fixation point − reaction time).

2.1.4. Procedure

Subjects were tested individually in a dimly lighted room. Deaf subjects were tested at Gallaudet University in Washington, DC, and hearing subjects at the University of Rochester, NY. The experimental environment and setup was the same for both subject groups. They were seated 40 cm from the center of the LCD display, and instructed to maintain fixation on the central fixation point (a crosshair) at all times. The subjects were instructed to respond to the target arrow by pressing the arrow key on the keyboard corresponding to the direction of the target arrow as quickly as possible, while maintaining a high level of accuracy. The practice block took approximately 3 min, and each experimental block approximately 6 min, for a total duration of 15 min.

2.2. Results

Following Fan et al. (2002), trials in which reaction time measurements exceeded 1,700 ms were considered to have timed-out and were not analyzed further (<0.1 percent of all responses). On a subject-by-subject basis a median reaction time (RT) was calculated for each of 12 conditions (3 flanker congruencies by 4 cue types) including only correct trials. Accuracy levels were computed for the same 12 conditions.

Data were collapsed across target direction (left/right) and target location (above/below). The overall pattern of data was considered by running omnibus ANOVAs on the reaction times. Separate ANOVAs were performed to compare (a) incongruent and neutral flanker conditions, and (b) congruent and neutral flanker conditions. It has been proposed that contrasting incongruent and neutral flanker conditions provides the best index of flanker interference effects (see Lavie, 1995, p. 454). While the processes underlying interference from incongruent and congruent flankers may differ, our hypothesis that enhanced peripheral attention in deaf signers leads to a stronger 'flanker signal' is compatible with enhanced interference and/or facilitation being observed in both comparisons. For this reason we also report the contrast between congruent and neutral flanker conditions.

In all cases, error analyses either replicated the effects observed with RTs or revealed null effects, thus will not be reported further (see Appendix for error tables).

2.2.1. Incongruent versus neutral flankers

The RT data (Table 1) were entered into a mixed ANOVA, with flanker congruency (neutral, incongruent) and cue type (none, center, double, spatial) as within subjects factors, and deafness (deaf, hearing) as a between subjects factor. This revealed main effects of cue type ($F(3, 93) = 65.27$, $p < .001$, $\eta_p^2 = .678$), flanker congruency ($F(1, 31) = 359.47$, $p < .001$, $\eta_p^2 = .921$), and a significant interaction between flanker and cue type ($F(3, 93) = 11.13$, $p < .001$, $\eta_p^2 = .264$). Although deafness did not interact with any of the other factors (all $F < 1$), there was a marginally significant main effect of deafness ($F(1, 31) = 4.02$,

Table 1
Mean (*SD*) reaction time for deaf and hearing subjects by flanker congruency and cue type, Experiment 1

Experiment 1	Cue type			
	None	Center	Double	Spatial
Deaf ($n = 17$)				
Incongruent	649 (101)	641 (114)	632 (99)	595 (99)
Congruent	560 (60)	521 (71)	526 (75)	495 (63)
Neutral	552 (64)	504 (59)	507 (68)	488 (68)
Hearing ($n = 16$)				
Incongruent	617 (54)	603 (45)	584 (35)	543 (52)
Congruent	516 (58)	473 (37)	471 (37)	451 (43)
Neutral	505 (42)	467 (32)	455 (36)	440 (33)

$p = .054$, $\eta_p^2 = .115$). Overall, deaf subjects ($M = 571$ ms) took 44 ms longer to respond than did hearing subjects ($M = 527$ ms).

2.2.1.1. Cue type effect. The main effect of cue type highlights differences between cues. Following the existing literature, planned contrast of the alerting (double versus no cue) and orienting (center versus spatial cue) were carried out. These planned contrasts revealed (a) a main effect of alerting ($F(1, 31) = 42.56$, $p < .001$, $\eta_p^2 = .579$) and (b) a main effect of orienting ($F(1, 31) = 80.44$, $p < .001$, $\eta_p^2 = .722$). The lack of any interaction with deafness suggests that alerting and orienting processes are equivalent for deaf and hearing subjects (see Fig. 2).

2.2.1.2. Flanker interference effect. The main effect of flanker congruency reported above is due to longer RTs for the incongruent flanker conditions than for the neutral flanker condition. Unlike what would be expected from greater peripheral attention in deaf individuals, the flanker interference effect did not significantly interact with deafness. This lack of interaction is further addressed in Experiment 2.

2.2.1.3. Interaction between flanker interference and cue type. The two-way interaction between flanker congruency and cue type indicates that spatially uninformative cues (central or double cue) lead to greater flanker interference effects than either no cue or spatially informative cues (see Fig. 2).

2.2.2. *Congruent versus neutral flankers*

Repeating the analysis of RTs comparing congruent and neutral flanker conditions with cue type (none, center, double, spatial) as a within subjects factor and deafness (deaf, hearing) as a between subjects factor, revealed significant main effects of cue type ($F(3, 93) = 91.37$, $p < .001$, $\eta_p^2 = .747$), flanker congruency ($F(1, 31) = 25.37$, $p < .001$, $\eta_p^2 = .450$) and deafness ($F(1, 31) = 6.65$, $p = .015$, $\eta_p^2 = .177$), revealing similar effects as in the analysis of incongruent versus neutral flankers. In particular, planned contrasts revealed significant orienting ($F(1, 31) = 87.28$, $p < .001$, $\eta_p^2 = .738$) and alerting effects ($F(1, 31) = 34.36$, $p < .001$, $\eta_p^2 = .526$) but no interaction with deafness indicating, again, comparable alerting and orienting effects in the two populations. The congruent flankers resulted in a flanker interference effect, and no interaction with deafness as in the previous analyses. Although RTs for congruent flanker trials were longer than for neutral flanker trials, a pattern that does not reflect the standard view of congruent flankers being facilitatory, a host of studies have reported such "negative" congruency effects (Bavelier, Deruelle & Proksch, 2000; van Leeuwen & Lachmann 2004; and see Lavie, 2005). The discussion of whether congruent flankers should be facilitatory or inhibitory with respect to a neutral baseline is beyond the scope of this paper. For now, we just note that the interactions between interference effects and deafness are not obtained for both incongruent and congruent flankers comparisons.

2.3. *Discussion*

2.3.1. *Alerting and orienting*

The key findings reported by Fan et al. (2002) were replicated in this experiment. Subjects were able to use temporal (alerting) and spatial (orienting) information provided by cues to enhance their performance. Importantly, these effects of cue type did not interact with deafness. The finding of comparable effects of orienting cues in hearing and deaf individuals extends previous work using variants on the Posner cueing paradigm that also found that deaf individuals do not benefit more from valid orienting cues than do hearing individuals (Darves et al., 2003; Parasnis, 1992; Parasnis & Samar, 1985). Our data suggest that,

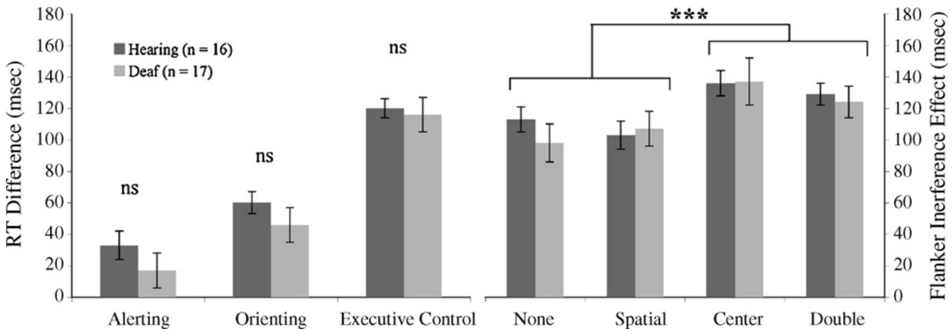

Fig. 2. Effects of cue type on RTs and its interaction with the flanker interference effect (incongruent vs. neutral comparison) from Experiment 1. The left panel illustrates the significant effects of alerting (no cue—double cue), orienting (center cue—spatial cue) and executive control (incongruent flanker—neutral flanker) for deaf and hearing subjects. The right panel shows the flanker interference effect broken down by cue type. Incongruent flankers interfered with responses more following center/double cues than following spatial cues or no cue at all.

in addition, alerting cues have comparable effects on deaf and hearing individuals.

2.3.2. *Executive control*

The ANT measures the efficiency of executive control by computing a flanker interference effect. When incongruent flankers surrounded a target, response latencies increased. The finding of comparable flanker interference effects between deaf and hearing subjects is more surprising. Although it is in agreement with reports in the literature that deaf and hearing individuals perform similarly when tested in central vision (Loke & Song, 1991; Stevens & Neville, 2006), the enhanced peripheral attention previously reported in the literature also predicts greater distractibility from peripheral distractors in deaf as compared to hearing individuals. Indeed, an increased attentional focus in the periphery is expected to lead to increased salience and processing of flankers, and thus result in a larger flanker interference effect from the peripheral arrow flankers. For example, Sladen et al. (2005), also using a central task, reported greater flanker interference effects for deaf subjects from flankers positioned at 1.0° and 2.0° than at 0.05° and 0.1°. Although this effect was small and not sustained at a greater eccentricity (3.0° and 6.0°), Experiment 2 asks whether deaf and hearing individuals may differ in the magnitude of their flanker interference effects as the eccentricity of the flankers is manipulated.

2.3.3. *Interactions between attentional networks*

There was also a significant interaction between the type of flanker presented and the nature of the cue. As reported by Fan et al. (2002) and Callejas et al. (2005), flanker interference effects were larger in the presence of alerting cues (center or double cues) and smaller in the presence of an orienting cue (spatial cue). The interaction between flanker congruency and cue type can be understood using an ‘attentional spotlight’ metaphor for the distribution of attention across the stimulus display, whereby the alerting and orienting cues serve to facilitate activity at different spatial scales (see Hopf et al., 2006). The alerting cue (center or double) serves to focus attention on the upcoming stimulus display, but does not provide enough spatial information about the target location and thus brings not only the target but also the flankers into a zone of heightened attention. As a result, the target and flankers are both processed to a greater extent than in the no-cue condition, accounting for the larger flanker interference effects. In contrast, an orienting cue helps direct the subject’s attention to the spatial location of the target. In doing so, it helps the subject spatially segregate the target from the flankers—the flankers now fall outside of the zone of heightened attention and compete less for a response; as a result smaller flanker interference effects are observed (see Fernandez-Duque & Posner, 1997 for a similar discussion).

3. Experiment 2

In Experiment 1, flanker interference effects were comparable for deaf and hearing subjects. Experiment 2 extended the ANT paradigm with modifications to the stimulus display designed to increase the probability of detecting a population difference in the spatial distribution of attention (Fig. 3). Specifically, by positioning the flankers at different spatial locations along the horizontal meridian (in a similar manner to Sladen et al., 2005) a greater range of eccentricities were tested. The flankers (incongruent, congruent or neutral) were located 1.0°, 2.0° or 3.0° of visual angle from the center of the target stimulus. In addition, the number of flankers surrounding the target was reduced from four to two. A recent study by Kerzel, Weigelt, and Bosbach (2006) suggests a non-linear relationship between the amount of incongruent flanker information available and the size of the flanker interference effect, with four incongruent flankers saturating the size of the effect. Thus the lack of an observed difference in flanker interference effects between deaf and hearing subjects may be the result of ceiling effects. A reduction in the amount of incongruent information available should therefore increase the chance of detecting between group differences. Finally, empty locations in the stimulus array were filled with horizontal lines to equalize crowding across eccentricity conditions (Fig. 3).

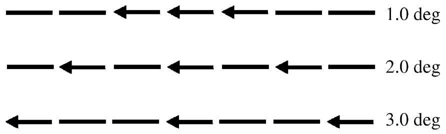

Fig. 3. In Experiment 2, the distance between the target and flanking arrows was manipulated. Two flankers were positioned equidistant from the target arrow, with one flanker on each side. The center of the flanking arrows was positioned at 1.0°, 2.0° or 3.0° of visual angle from the center of the target arrow.

3.1. *Method*

3.1.1. *Subjects*

Forty subjects participated in the study. Subjects who reported playing any action video games in the previous 12 months were excluded from analyses (two deaf males, one deaf female). In addition, one deaf subject did not complete testing and was excluded, and one other had an unusually high overall error score (>25 percent) and was also excluded from analyses. Of the 35 remaining subjects included in the analyses, 15 were deaf signers aged 18–26 years ($M = 22$, $SD = 2$, 3 males) all of whom were born profoundly deaf to deaf parents. All deaf subjects had been exposed to and acquired ASL as a first language from birth, and had a 90 dB or greater loss in their better ear. Twenty subjects had normal hearing, and were 19–27 years of age ($M = 21$, $SD = 2$, 3 males). All spoke only English and reported no exposure to ASL.

All subjects had normal or corrected-to-normal vision, no reported history of neurological impairment, and were right-handed. They were naïve to the aims of the study and paid for their participation. All subjects gave written informed consent and the protocols were given ethical approval by the University of Rochester Research Subjects Review Board and the Gallaudet University Institutional Review Board.

3.1.2. *Apparatus and materials*

Same as Experiment 1.

3.1.3. *Stimuli and design*

There was one between subjects factor (*deafness*—deaf, hearing) and three within subjects factors (*flanker congruency*—incongruent, congruent, neutral, *cue type*—none, center, double, spatial, and *flanker eccentricity*—1.0°, 2.0° and 3.0°). Different flanker eccentricities were run in separate blocks, with the order of block presentation counterbalanced across subjects. There were 192 trials for each flanker eccentricity. A block of 24 practice trials preceded the experimental blocks, giving a total of 648 trials. The timings within each trial were the same as in Experiment 1.

Each stimulus subtended 0.9° of visual angle, with the edges of adjacent stimuli separated by 0.1° of visual angle (see Fig. 3). All other aspects were identical to Experiment 1.

3.1.4. *Procedure*

The procedure from Experiment 1 was followed for each level of flanker eccentricity. Testing took approximately 1 h.

3.2. *Results*

The same criteria employed in Experiment 1 were used to select RT and accuracy data for analysis. For each subject, a median RT was calculated for each of 36 conditions (3 flanker congruencies by 4 cue types by 3 flanker eccentricities).

The remaining data were analyzed in the same way as in Experiment 1.

3.2.1. *Omnibus ANOVA*

3.2.1.1. Incongruent and neutral flankers. The RT data (Table 2) were entered into a mixed ANOVA, with flanker eccentricity (1.0°, 2.0° or 3.0°), flanker congruency (neutral, incongruent) and cue type (none, center, double, spatial) as within subjects factors, and deafness (deaf, hearing) as a between subjects factor. As in Experiment 1, this analysis revealed main effects of cue type ($F(3, 99) = 226.80$, $p < .001$, $\eta_p^2 = .873$), flanker congruency ($F(1, 33) = 437.67$, $p < .001$, $\eta_p^2 = .930$). and a two-way interaction between flanker congruency and cue type ($F(3, 99) = 17.30$, $p < .001$, $\eta_p^2 = .344$). In addition, there was a main effect of flanker eccentricity ($F(2, 66) = 101.33$, $p < .001$, $\eta_p^2 = .754$), a significant two-way interaction between flanker eccentricity and flanker congruency ($F(2, 66) = 148.39$, $p < .001$, $\eta_p^2 = .818$) and a three-way interaction between flanker eccentricity, flanker congruency and cue type ($F(6, 198) = 3.47$, $p = .003$, $\eta_p^2 = .095$). Finally, there was a significant main effect of deafness ($F(1, 33) = 8.54$, $p = .006$, $\eta_p^2 = .206$) which crucially, and unlike in Experiment 1, interacted significantly with flanker congruency ($F(1, 33) = 5.75$, $p = .022$, $\eta_p^2 = .148$)

Table 2
Mean (*SD*) reaction time for deaf and hearing subjects by flanker eccentricity, flanker congruency and cue type, Experiment 2

Experiment 2	Cue type			
	None	Center	Double	Spatial
Deaf ($n = 15$)				
Flanker eccentricity 1.0°				
Incongruent	663 (35)	655 (72)	634 (34)	587 (64)
Congruent	575 (47)	522 (47)	520 (48)	495 (44)
Neutral	552 (41)	494 (38)	496 (45)	477 (38)
Flanker eccentricity 2.0°				
Incongruent	564 (21)	554 (38)	534 (40)	505 (46)
Congruent	538 (33)	490 (37)	488 (32)	465 (39)
Neutral	523 (27)	481 (39)	470 (34)	451 (29)
Flanker eccentricity 3.0°				
Incongruent	565 (45)	521 (39)	514 (34)	492 (49)
Congruent	534 (55)	478 (43)	480 (38)	456 (45)
Neutral	525 (40)	467 (38)	473 (45)	449 (41)
Hearing ($n = 20$)				
Flanker eccentricity 1.0°				
Incongruent	611 (65)	591 (51)	579 (64)	523 (60)
Congruent	527 (55)	482 (56)	478 (51)	444 (42)
Neutral	508 (51)	465 (49)	459 (42)	440 (47)
Flanker eccentricity 2.0°				
Incongruent	537 (48)	511 (50)	491 (52)	450 (48)
Congruent	507 (46)	460 (47)	454 (49)	428 (48)
Neutral	504 (48)	448 (42)	448 (51)	420 (32)
Flanker eccentricity 3.0°				
Incongruent	528 (64)	491 (59)	471 (66)	442 (49)
Congruent	497 (56)	454 (48)	446 (47)	424 (45)
Neutral	490 (57)	442 (45)	446 (48)	418 (41)

3.2.1.1.1. Cue type effect. As in Experiment 1, planned contrasts were performed to document alerting and orienting effects. Main effects of alerting ($F(1, 33) = 333.81$, $p < .001$, $\eta_p^2 = .910$) and orienting ($F(1, 33) = 180.69$, $p < .001$, $\eta_p^2 = .846$) were observed that did not interact with group (see Fig. 4).

3.2.1.1.2. Flanker interference effect. As in Experiment 1, incongruent flankers lead to longer RTs compared to neutral flankers, more so for center and double cue trials than for no cue and spatial cue trials. Furthermore, the three-way interaction between flanker eccentricity, flanker congruency and cue type

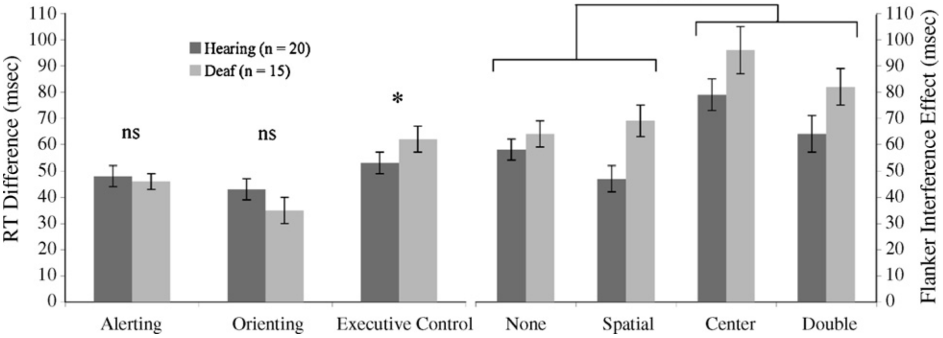

Fig. 4. Effects of cue type on RTs and its interaction with the flanker interference effect (incongruent vs. neutral comparison) from Experiment 2. The left panel illustrates the significant effects of alerting (no cue—double cue), orienting (center cue—spatial cue) and executive control (incongruent flanker—neutral flanker) for deaf and hearing subjects. The right panel show the flanker interference effect broken down by cue type. As reported in Experiment 1, incongruent flankers interfered with responses more following center/double cues than following spatial cues or no cue at all.

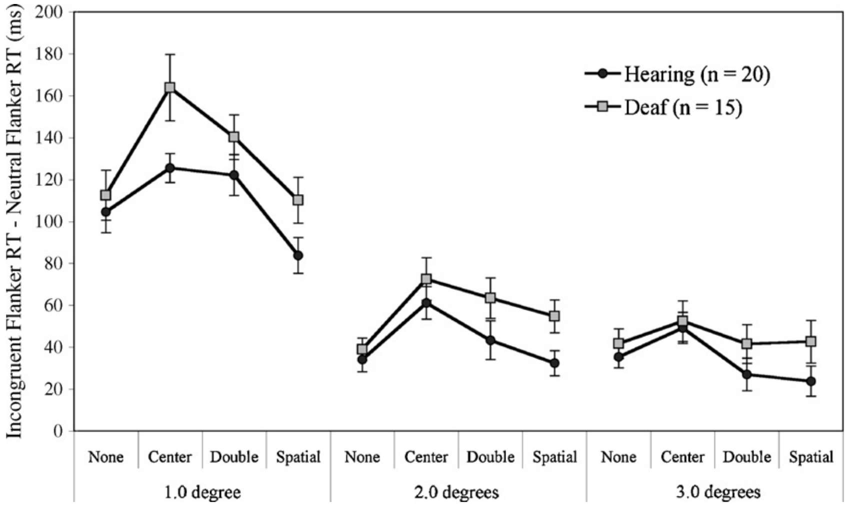

Fig. 5. The flanker interference effect as a function of cue type across all eccentricities for each population. Two main effects can be noted: (1) the flanker interference effects decreases as eccentricity increases and (2) over all eccentricities tested, deaf individuals demonstrate greater flanker interference.

indicated that as flankers were moved further into the periphery, the effect of cue type on the size of the flanker interference effect diminished (see Fig. 5). Importantly, and unlike Experiment 1, the interaction between flanker congruency and deafness reflected a larger flanker interference effect for deaf subjects than for hearing subjects (see Fig. 5).

3.2.1.2. Congruent and neutral flankers. Repeating the analysis but comparing congruent and neutral flanker conditions revealed a pattern of findings very similar to that obtained in the incongruent–neutral analysis, with significant main effects of cue type ($F(3, 99) = 224.10$, $p < .001$, $\eta_p^2 = .872$) and flanker congruency ($F(1, 33) = 72.49$, $p < .001$, $\eta_p^2 = .687$). There was also a significant main effect of flanker eccentricity ($F(2, 66) = 26.58$, $p < .001$, $\eta_p^2 = .446$), and a significant two-way interaction between flanker eccentricity and flanker congruency ($F(2, 66) = 13.60$, $p < .001$, $\eta_p^2 = .292$). Incongruent flankers resulted in slower RTs compared to neutral flankers. At larger eccentricities, responses were faster and flanker interference effects were smaller.

As in the previous analyses, planned contrasts on cue-type effects revealed main effects of alerting ($F(1, 33) = 239.93$, $p < .001$, $\eta_p^2 = .879$) and orienting ($F(1, 33) = 127.93$, $p < .001$, $\eta_p^2 = .795$) which did not interact with group, supporting the view that alerting and orienting effects are comparable in deaf and hearing populations.

Finally, there was a main effect of deafness ($F(1, 33) = 6.85$, $p = .013$, $\eta_p^2 = .172$) which crucially, and unlike in Experiment 1, interacted with flanker congruency ($F(1, 33) = 4.87$, $p = .034$, $\eta_p^2 = .129$) revealing greater flanker interference effects for deaf than for hearing individuals. No other effects reached statistical significance.

3.3. Discussion

Deaf and hearing subjects benefited equally from alerting and orienting cues, reinforcing the view that the alerting and orienting networks are comparable across groups. Second, as described in Experiment 1, the type of flanker interacted with the nature of the cue whereby the flanker interference effect was greater following alerting cues (central and double cues) than after an orienting cue (spatial cue) or no cue at all. Importantly, these effects were modulated by eccentricity in accordance with the view that the nature of the cue changes the scale of the distribution of attention over the display. As expected under this view, the influence of alerting and orienting cues on performance was diminished as flankers were positioned further into periphery. Finally, and unlike in Experiment 1, an effect of deafness on flanker interference effect sizes was observed in Experiment 2. As expected from enhanced peripheral attention in deaf individuals, deaf subjects exhibited larger flanker interference effects than hearing subjects from peripherally located flankers. This population difference in flanker interference effect size did not statistically diminish with eccentricity, suggesting that the difference in attentional resources across groups is maintained across the small range of eccentricities tested. It is, however, unclear whether the reallocation of attention to the periphery in deaf individuals extends uniformly across 1.0–3.0° of visual angle, or decreases after 3.0° of eccentricity as Sladen et al. (2005) report. Studies using other paradigms have reported differences in peripheral visual attention between deaf and hearing individuals at greater eccentricities, ranging from 4.5° all the way to 35° and above (Bavelier et al., 2001; Loke & Song, 1991; Proksch & Bavelier, 2002; Stevens & Neville, 2006).

4. General discussion

4.1. Alerting and orienting are not affected by deafness

The ANT appears to be a reliable tool for the assessment of alerting and orienting processes. Key effects of cue type have been described in hearing adults (Callejas et al., 2004; Fan et al., 2002) and in children (Rueda et al., 2004) documenting how different aspects of attention guide performance across age. We show here that these two aspects of attention are comparable across deaf and hearing individuals. In two sepa-

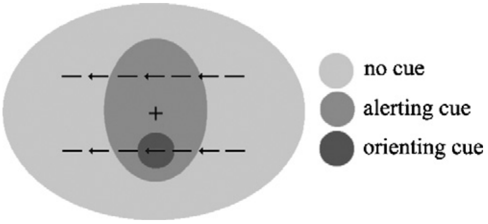

Fig. 6. The data from both experiments can be parsimoniously explained using a simple 'spotlight' metaphor of visual attention, which does not require mechanistic interactions between alerting, orienting and executive control networks to be proposed. By default, visual attention is spread over the entire visual display (light grey outer area of the figure). An alerting (double) cue serves to focus attention in on the center of the display, but the attentional spotlight still encompasses flankers that are proximal to the potential target locations (medium grey area). A valid orienting (spatial) cue further restricts the spotlight to the impending target's spatial location. Thus, an alerting cue does not provide as much assistance to the observer when flankers are incongruent—conflict resolution between the competing responses elicited by target and flanker arrows is still required. However, an orienting cue provides a large benefit in such conditions, by focusing upon the target at the expense of the competing flanker information—this benefit is most acute when those competing flanker arrows are closer to the target.

rate experiments, deaf individuals displayed the same benefits from alerting and orienting cues as seen in hearing individuals supporting the view that early deafness does not fundamentally alter the characteristics of these attentional processes.

4.2. *Alerting and orienting cues modulate flanker interference effects*

The results of the present experiments highlight the presence of robust interactions between flanker congruency and cue type. Specifically, it was observed that the presence of alerting and orienting cues modulated the size of flanker interference effects from incongruent flankers.

In the case of alerting, the presence of an alerting cue resulted in larger flanker interference effects (Experiments 1 and 2), a phenomenon reported by several other authors (Callejas et al., 2004, 2005; Fan et al., 2002; Fernandez-Duque & Black, 2006; Funes & Lupianez, 2003; Rueda et al., 2004). The commonly accepted interpretation for this alerting effect is that it shifts response criteria thus producing faster responses that operate upon incomplete information (a view supported by Fernandez-Duque & Black, 2006). This interpretation appears insufficient to fully explain the findings of Experiment 2 in which positioning flankers at increasing eccentricities reduced the influence of the alerting cue on flanker interference. This latter effect can be readily captured however by also taking into account the spatial scale of attention that an alerting cue enforces when modeling the alerting effect (the medium grey zone in Fig. 6). In the absence of a cue, attention is spread diffusely over a large area allowing for only limited attentional resources to be attributed to targets and flankers. An alerting cue narrows this distribution over the possible target locations, thereby decreasing response times to the target but also increasing the disruptive effects of nearby flankers as those are also located in the zone of heightened attentional resources and thus compete to a greater extent with target processing (Lavie, 2005). However, as flankers are moved further away from the target, flankers move outside of the attentional zone created by the alerting cue, and therefore exert less influence on processing.

A very similar explanation can account for the variation in the size of the flanker interference effects attributable to orienting cues. As demonstrated by Experiments 1 and 2, the presence of an orienting cue resulted in a smaller flanker interference effect as compared to a central cue. In addition, as the distance of the incongruent flankers from the target was increased, the benefit obtained from the orienting cue diminished. As in the case of alerting, these interactions can be explained using an 'attentional spotlight' metaphor for the distribution and control of visual attention. The orienting cue (a valid spatial cue) focuses attention tightly on the location of target (the central, dark grey, zone in Fig. 6), resulting in a speeding of target processing (the orienting effect) and easier flanker exclusion, reducing response conflict relative to conditions in which a center cue is present (the medium grey zone in Fig. 6). The benefit of the orienting cue over a central cue is lessened when the eccentricity of the flankers increases, because as flankers are moved further away from the target they move outside of the attentional zone. As a result, at more distal flanker locations the only benefit observed is that of enhanced target processing, which is equivalent for all flanker congruencies.

This spatial metaphor for the distribution of visual attention allows us to interpret the interactions between alerting/orienting cues and response conflict in terms of the spatial distribution of attention. Specifically, the alerting and orienting cues serve to modulate the salience of the flankers. Importantly, these effects are observed for both deaf and hearing individuals. Thus, while we argue that a redistribution of attention to the periphery results from early loss of the auditory modality, the mechanisms underlying the dynamic allocation of attention to abrupt-onset stimuli do not appear to be affected by deafness.

4.3. *Deaf subjects are more susceptible to peripheral distractors*

Deaf individuals displayed greater susceptibility than hearing individuals to both incongruent and congruent flankers located in the periphery. Although it is unclear why this effect was not noted in Experiment 1, Experiment 2 tested a wider range of flanker eccentricities (1.0°, 2.0° and 3.0°) and established significantly larger flanker interference effects in deaf individuals than in hearing individuals. The observed size of the effect of deafness on flanker interference effects is relatively small in terms of milliseconds, ranging from 12 ms at 1.0° to 7 ms at 3.0°. However, these values represent modest-to-large effect sizes, with Cohen's *d* values for the group differences in flanker interference effects ranging from .5 to .7 at the different eccentricities tested.

Although greater flanker interference effects are typically interpreted as markers of poorer executive control, previous research with deaf individuals indicates that this is an unlikely explanation in this case. Rather, in previous studies, a shift in the spatial distribution of visual attention in deaf individuals has been documented, whereby attentional resources are heightened in the visual periphery and slightly decreased in central vision in deaf as compared to hearing individuals (Bavelier, Tomann et al. 2000; Bavelier, Dye, & Hauser, 2006; Proksch & Bavelier, 2002; Sladen et al., 2005). As a result of this shift, deaf individuals exhibited greater flanker interference effects from peripheral flankers than hearing individuals, but hearing individuals exhibited greater flanker interference effects from central distractors than deaf individuals. This pattern of findings established that it is not just the case that deaf individuals cannot apply appropriate executive control to filter out flankers, but rather that the spatial distribution of attentional resources differ in deaf and hearing individuals. Although the ANT design does not allow a contrast of central versus peripheral flankers, the finding of greater flanker interference effects in deaf than in hearing individuals (across all peripheral flanker locations tested and for both incongruent and congruent flankers) is in line with the proposal of heightened peripheral attention in deaf individuals.

In summary, the studies reported here establish no difference between hearing and deaf subjects in the ‘efficiency’ of two of the attentional networks measured by the ANT—alerting and orienting. As predicted by a redistribution of visual attention to the periphery as a result of early deafness, larger flanker interference effects were observed for deaf than for hearing individuals. This pattern of findings highlights the specificity of the changes in visual attention following early deafness, with the spatial distribution of attention being altered by early deafness, but alerting and orienting processes showing little sensitivity to sensory deprivation.

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Appendix A. Error tables

Tables A1 and A2.

Table A1
Mean (*SD*) percentage error for deaf and hearing subjects by flanker congruency and cue type, Experiment 1

Experiment 1	Cue type			
	None	Center	Double	Spatial
Deaf (*n* = 17)				
Incongruent	1.2 (2.7)	1.6 (3.8)	3.7 (6.1)	1.5 (4.3)
Congruent	.0 (.0)	.0 (.0)	.0 (.0)	.8 (2.2)
Neutral	1.6 (3.7)	.8 (2.2)	.0 (.0)	.0 (.0)
Hearing (*n* = 16)				
Incongruent	2.5 (3.4)	.5 (1.9)	5.1 (7.2)	2.9 (7.3)
Congruent	.0 (.0)	.0 (.0)	.0 (.0)	.8 (2.2)
Neutral	.4 (1.6)	.4 (1.7)	.0 (.0)	.4 (1.7)

Table A2
Mean (*SD*) error rates (percent) for deaf and hearing subjects by flanker eccentricity, flanker congruency and cue type, Experiment 2

Experiment 2	Cue type			
	None	Center	Double	Spatial
Deaf (*n* = 15)				
Flanker eccentricity 1.0°				
Incongruent	5.3 (5.7)	6.7 (11.1)	7.3 (9.4)	2.6 (3.3)
Congruent	.4 (1.7)	.0 (.0)	.0 (.0)	.0 (.0)
Neutral	.4 (1.7)	.9 (2.4)	.0 (.0)	.0 (.0)
Flanker eccentricity 2.0°				
Incongruent	2.2 (3.2)	4.0 (3.4)	4.0 (4.2)	.4 (1.7)
Congruent	1.7 (3.8)	.4 (1.7)	.9 (2.4)	.4 (1.7)
Neutral	1.4 (2.8)	1.3 (3.7)	.4 (1.7)	.4 (1.7)
Flanker eccentricity 3.0°				
Incongruent	4.0 (4.2)	2.5 (4.0)	2.6 (4.2)	.4 (1.7)
Congruent	.0 (.0)	.4 (1.6)	.0 (.0)	.4 (1.7)
Neutral	1.3 (2.8)	.0 (.0)	.4 (1.7)	.9 (2.4)
Hearing (*n* = 20)				
Flanker eccentricity 1.0°				
Incongruent	6.6 (10.5)	10.5 (14.8)	5.7 (8.5)	6.4 (7.4)
Congruent	1.0 (2.4)	.0 (.0)	.7 (2.1)	1.0 (2.4)
Neutral	.0 (.0)	.3 (1.5)	.3 (1.5)	.7 (2.1)
Flanker eccentricity 2.0°				
Incongruent	3.9 (7.2)	4.4 (6.3)	2.7 (4.0)	2.7 (4.0)
Congruent	.3 (1.5)	.7 (2.0)	.7 (2.1)	.7 (2.1)
Neutral	.7 (2.1)	1.7 (3.7)	1.0 (2.4)	.6 (1.9)
Flanker Eccentricity 3.0°				
Incongruent	1.0 (3.1)	4.4 (5.9)	3.2 (4.9)	2.3 (3.3)
Congruent	1.3 (2.8)	1.3 (3.4)	2.7 (4.5)	2.3 (3.8)
Neutral	1.0 (2.5)	.3 (1.4)	.7 (2.0)	1.3 (4.1)

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