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Changes in the Spatial Distribution of Visual Attention after Early Deafness

Jason Proksch and Daphne Bavelier

Abstract

■ There is much anecdotal suggestion of improved visual skills in congenitally deaf individuals. However, this claim has only been met by mixed results from careful investigations of visual skills in deaf individuals. Psychophysical assessments of visual functions have failed, for the most part, to validate the view of enhanced visual skills after deafness. Only a few studies have shown an advantage for deaf individuals in visual tasks. Interestingly, all of these studies share the requirement that participants process visual information in their peripheral visual field under demanding conditions of attention. This work has led us to propose that congenital auditory deprivation alters the gradient of visual attention from central to peripheral field by enhancing peripheral processing. This hypothesis was tested by adapting a search task from Lavie and colleagues in which the interference from distracting information on the search task provides a measure of attentional resources. These authors have established that during an easy central search for a target, any surplus attention remaining will involuntarily process a peripheral distractor that the subject has been instructed to ignore. Attentional resources can be measured by adjusting the difficulty of the search task to the point at which no surplus resources are available for the distractor. Through modification of this paradigm, central and peripheral attentional resources were compared in deaf and hearing individuals. Deaf individuals possessed greater attentional resources in the periphery but less in the center when compared to hearing individuals. Furthermore, based on results from native hearing signers, it was shown that sign language alone could not be responsible for these changes. We conclude that auditory deprivation from birth leads to compensatory changes within the visual system that enhance attentional processing of the peripheral visual field. ■

INTRODUCTION

Anecdotal information suggests that deaf individuals may display improvements in their remaining senses. However, the current literature has not provided clear support for this claim. These mixed results have led to the development of two competing theories regarding the origin and nature of changes in visual functions observed after auditory deprivation. The "deficiency theory" holds that integrative processes are essential for normal development. In this view, multisensory integration is critical for the full development of each sensory modality (Radell & Gottlieb, 1992; Turkewitz & Kenny, 1982). Deprivation in one sense is believed to result in deficiencies in the other senses. In contrast, the "compensatory theory" states that the loss of one sense may be met by a greater reliance upon, and therefore an enhancement of, the remaining senses (Grafman, 2001; Neville, 1990).

Investigations of psychophysical thresholds within the visual domain in deaf subjects have failed to validate the anecdotal suggestion of better thresholds in sensory deprived subjects, such as congenitally deaf individuals. In a forced choice brightness discrimination task, deaf subjects showed no significant difference in their thresholds from that of hearing subjects (Bross, 1979). Similarly, visual contrast sensitivity has recently been shown to be equivalent between deaf and hearing individuals (Finney & Dobkins, 2001). Temporal processing also appears comparable in these two populations as tested by temporal discrimination thresholds (Mills, 1985) and temporal resolution (Poizner & Tallal, 1987; Bross & Sauerwein, 1980). Finally, although discrimination thresholds for motion direction have revealed a lateralization difference between deaf signers and hearing controls, no overall enhancement of the sensitivity of motion processing has been observed in the deaf (Bosworth & Dobkins, 1999). Since the same lateralization difference has been reported between hearing controls and hearing native signers (i.e., individuals born to deaf parents, and exposed to sign language from birth), this pattern appears driven by early signing exposure rather than deafness per se (Bavelier et al., 2001; Neville & Lawson, 1987c).

There have been multiple reports claiming that deaf subjects have no enhancement and possibly exhibit impairments at later stages in visual processing. For example, early studies report that deaf children perform worse than their hearing counterparts on the Keystone visual survey (Myklebust, 1950; Myklebust &

Brutten, 1953), the Marble Board Test, figure and ground tests, and tachistoscopically presented materials (Werner & Strauss, 1942). More recently, Netelenbos and Savelsbergh (1991) performed an experiment where children (mean age 10 years old) were asked to focus on a target presented at various eccentricities up to 90° from initial fixation. Results for the deaf and hearing were identical, except when the initial saccade was incorrect and gaze had to be redirected to the other side. In this case, deaf children were slower to redirect their gaze. Another report of impaired visual processing comes from an experiment by Quittner, Smith, Osberger, Mitchell, and Katz (1994). Children between the ages of 9 and 13 were instructed to look for a prespecified two-digit sequence in a serially presented stream of digits. The deaf children made more errors than the hearing children suggesting greater difficulty to ignore the irrelevant stimuli in the deaf population.

While a large number of experiments suggest no change or deficiency in deaf individuals' visual performance, a few studies have revealed enhanced visual performance with complex visual tasks, especially when visual attention and/or the processing of the peripheral visual field was manipulated. Loke and Song (1991) have shown that deaf adults are faster at detecting the onset of a peripheral character. Neville and Lawson (1987a, 1987b) have shown that, with attention to peripheral stimuli, evoked potentials in deaf subjects display attention related increases that are several times larger than those from hearing subjects, whereas the two populations are comparable for central stimuli. In a recent fMRI study, Bavelier et al. (2001) have observed that deaf participants are better at detecting changes in a moving pattern when the changes are located peripherally rather than centrally, whereas hearing participants showed the reverse trend. Additionally, this behavioral effect was mirrored by an enhanced recruitment of the motion area MT/MST in deaf subjects as compared to hearing controls when visual attention was distributed to the periphery. Together, these results suggest enhanced peripheral attention in the deaf (Bavelier et al., 2000, 2001). In accordance with the view of alterations within the attentional system, Rettenbach, Diller, and Sireteanu (1999) and Stivalet, Moreno, Richard, Barraud, and Raphel (1998) have shown that deaf individuals are more efficient during visual search tasks. This population advantage was especially robust on the target-absent trials; in other words, deaf subjects were able to terminate their search faster when no target was presented without compromising their accuracy. Importantly, this skill has recently been linked to an enhanced capacity at distributing attention over the whole visual field (Sireteanu & Rettenbach, 2000). The proposal that visual attention and peripheral processing are enhanced by deafness is also in line with a few studies suggesting a

different allocation of visual attention when central and peripheral fields compete for attentional resources. Reynolds (1993) has reported that deaf individuals tend to be better than hearing individuals at detecting the onset of a peripheral stimulus in the presence of competing central stimuli. Similarly, Parasnis and Samar (1985) have shown that deaf subjects are faster at redirecting their visual attention toward the correct peripheral location when initially cued to the wrong location in the presence of competing central stimuli.

Thus, the common feature across all the studies that report enhanced visual functions in the deaf appears to be the manipulation of peripheral vision and visual attention. This observation is compatible with two main hypotheses. On the one hand, deafness may lead to better peripheral vision. For example, the representation of the peripheral field found in early visual areas might have expanded, thus endowing peripheral vision with a greater resolution in deaf individuals. On the other hand, deafness may lead to compensation in the mechanisms that allocate visual attention over the visual field. In particular, it may shift the preference for central allocation of attention found in hearing controls toward peripheral locations. In the absence of audition to orient to their extrapersonal space, deaf individuals may rely to a greater extent on vision to monitor their peripheral field, and thus to allocate attentional resources more readily to the visual periphery. These two hypotheses are not mutually exclusive, but crisp evidence for one or the other is at present elusive.

The goal of this study was to directly assess the hypothesis of a change in the spatial distribution of attention following early deafness. In particular, we hypothesize that deafness leads to an altered gradient of attention across the visual field, whereby attentional resources, which tend to be focused on the central field and to decrease quite steeply from the center to the periphery in hearing controls, are more equally distributed across the visual field in deaf subjects. To test this view, we studied the effect of distractors on a target identification task as the distractor location was varied between the center and the periphery.

We adapted a paradigm developed by Lavie and colleagues (Maylor & Lavie, 1998; Lavie & Cox, 1997; Rees, Frith, & Lavie, 1997; Lavie, 1995) to assess the extent of attentional resources at central and peripheral locations in hearing controls and deaf signers. In a typical version of this paradigm, subjects are to report the presence of one of two target letters in a ring of letters while ignoring a peripheral letter. This peripheral distractor can be either compatible with the target (the same letter), incompatible (the alternative target letter), or neutral (with no response association). The extent of processing of the distractor is inferred from the compatibility effect, or in other words, the interference of incompatible distractors as

compared to neutral and/or compatible distractors. Lavie and colleagues observed that the interference from distractors depended on the difficulty of the target task. The difficulty of the target task was varied based on the number of filler letters in the ring (see Figure 1B, e.g., with shapes). When the target task was easy (low load, few fillers), the distractor interfered with target identification leading to a sizeable compatibility effect whereby the incompatible distractor slowed target identification as compared to compatible or neutral distractors. However, when the target task was harder (high load, many fillers), the distractor did not interfere with target processing. These findings led Lavie and colleagues to propose a ''perceptual load hypothesis'': "With a low load in relevant processing, spare capacity inevitably spills over to process irrelevant information and hence may lead to distraction. Irrelevant processing can be prevented only when a high load in relevant processing exhausts capacity'' (Lavie & Cox, 1997).

This paradigm was adapted to test the proposal that attentional resources are distributed differently from center to periphery in hearing controls and deaf individuals. We reasoned that if deaf individuals have greater attentional resources than hearing individuals in the periphery, they should show a greater processing of irrelevant peripheral information, and thus, greater compatibility effects from peripheral distractors. Additionally, if deafness leads to a reallocation of the attentional resources available normally in the center to the periphery (without an overall increase in attentional resources), central attentional resources should be greater in hearing than deaf individuals and, thus central

distractors should be more distracting to hearing than to deaf individuals.

EXPERIMENT 1

To compare the distribution of attention in the hearing and deaf populations, Lavie's (1995) and Lavie and Cox's (1997) response competition paradigm was modified to include an eccentricity factor. Participants were asked to identify a target shape (square or diamond) as quickly as possible in one of six circular frames arranged in a ring around the fixation—the target zone (see Figure 1). A distracting shape was presented in either the center of the ring (central condition—0.5° from fixation to the left or right) or outside of the ring (peripheral condition—4.2° from fixation to the left or right). This distractor was either an element from the target set or a neutral shape, and was therefore compatible, incompatible, or neutral relative to the target. Subjects were instructed to ignore this distracting shape and focus on the target task. The work of Lavie and colleagues indicates that participants will process the distractor automatically unless attention is exhausted by the target task.

Although we will refer to the condition in which the distractor is presented at 4.2° from fixation as the peripheral condition, this eccentricity is better described as parafoveal. This layout was chosen to ensure that peripheral and central distractors were at a comparable distance from the target ring. This point is important if differences in effects between central and peripheral distractors are to be interpreted in terms of eccentricity rather than in terms of absolute distance. Indeed, it is well known that the compatibility effect
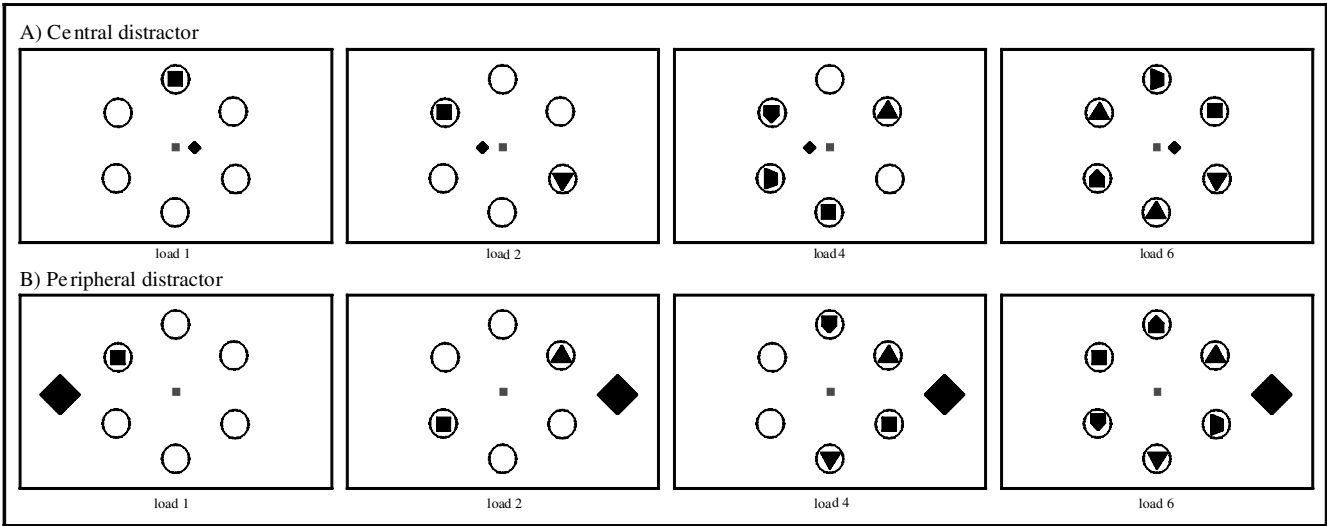
Figure 1. Example of stimuli used in Experiment 1. The participants' task was to decide as quickly and as accurately as possible if there was a square or a diamond in the target zone, defined by the six circular frames (examples of ''square'' targets are shown here). The difficulty of the task was systematically manipulated by adding more and more filler shapes in the target zone (load factor). The shape that does not appear in the target zone is termed the distractor. (A) The distractor is central. (B) The distractor is peripheral. Participants were explicitly instructed to ignore the distractor. The distractor shape could be neutral, compatible with the target, or incompatible with the target. Only incompatible distractors are exemplified here (the distractor is a ''diamond''). All shapes were sized to account for the cortical magnification factor.

measured in this study is highly sensitive to the distance between the target and the distractor (Miller, 1991; Eriksen & Eriksen, 1974).

The hypothesis of a change in the distribution of visual attention from the center to the periphery after early deafness led us to predict greater compatibility effects from ''peripheral'' distractors in the deaf, but greater compatibility effects from ''central'' distractors in the hearing. More specifically, we expected these effects to be present when the task was sufficiently difficult to have exhausted the attentional resources in one population but not the other. For example, in the case of peripheral distractors, both populations should show irrelevant processing of distractors when the target task is easy (low load). As the task difficulty is increased (by increasing load), peripheral attentional resources should exhaust in the hearing subjects, but still be available in the deaf subjects. Hence, there should be a range of task difficulties at which deaf individuals show greater processing of irrelevant peripheral distractors than hearing. Then as the task difficulty is increased further, capacity in deaf subjects should also eventually exhaust. Thus, the load manipulations in which attention has been exhausted in one population, but not the other, are of particular interest to our study. Because the critical load necessary to exhaust attentional resources is unknown, the stimulus load was manipulated by randomly including 0, 1, 3, or 5 filler shapes in the target zone. Therefore, the load (total number of items within the target zone) of each display was 1, 2, 4, or 6. The position of the target and any filler was random within the six radially located circles. The single distractor shape randomly appeared centrally or peripherally to the left or to the right; the size of the distractor was adjusted for cortical magnification.

With spare attentional resources, the distractor will be processed and will produce a compatibility effect. The design of this experiment was aimed at identifying any interaction of attentional resources between the two populations with regard to eccentricity. The load at which each population exhausts attentional resources is unknown and is likely to differ across the eccentricity manipulation.

Results

All analyses in this article relied on the use of a basic analysis of variance (ANOVA) model with reaction times

Table 1. RTs (Milliseconds) and Compatibility Effect (Mean ± Standard Error) at Each Load for Each Population and Distractor Eccentricity in Experiment 1

| Population	Load 1	Load 2	Load 4	Load 6
Central distractor				
Hearing				
Incompatible	690.3 ± 26.0 (5.9)	760.7 ± 23.6 (8.0)	842.5 ± 29.7 (15.0)	830.9 ± 35.3 (24.7)
Compatible	650.1 ± 21.1 (3.5)	724.1 ± 24.0 (6.3)	813.0 ± 30.5 (12.9)	828.7 ± 25.8 (23.0)
Compatibility effect	40.2 ± 8.9 (2.4)	36.6 ± 9.3 (1.7)	29.5 ± 11.7 (2.1)	2.2 ± 14.4 (1.7)
Deaf				
Incompatible	756.3 ± 37.6 (1.3)	802.2 ± 37.7 (4.2)	867.3 ± 39.7 (16.7)	904.9 ± 37.7 (19.6)
Compatible	710.3 ± 30.5 (2.1)	798.8 ± 35.9 (1.7)	871.6 ± 43.6 (10.0)	892.3 ± 37.4 (15.5)
Compatibility effect	46.0 ± 14.2 (1.8)	3.4 ± 8.7 (2.5)	−4.3 ± 19.1 (6.7)	12.6 ± 9.7 (4.1)
Peripheral distractor				
Hearing				
Incompatible	677.3 ± 19.8 (4.9)	742.6 ± 30.7 (8.0)	810.8 ± 33.2 (11.5)	832.7 ± 30.5 (26.1)
Compatible	640.5 ± 24.4 (0.4)	721.7 ± 24.5 (5.9)	815.7 ± 34.2 (10.5)	853.8 ± 29.8 (28.2)
Compatibility effect	36.8 ± 10.6 (4.5)	20.9 ± 11.4 (2.1)	−4.9 ± 17.4 (1.0)	−21.0 ± 12.6 (2.1)
Deaf				
Incompatible	756.4 ± 38.3 (5.9)	823.5 ± 37.8 (6.3)	886.4 ± 35.0 (15.0)	874.7 ± 45.6 (23.5)
Compatible	705.0 ± 29.2 (3.8)	790.6 ± 32.6 (3.8)	850.3 ± 38.1 (10.0)	887.7 ± 37.3 (17.5)
Compatibility effect	51.6 ± 13.6 (2.1)	32.9 ± 8.6 (2.5)	36.1 ± 13.9 (5.0)	−13.0 ± 17.2 (6.0)

The percentage of error is given in parenthesis for each condition.

(RTs) as the dependent variable and with population (hearing and deaf) as a between-subjects factor. First, an omnibus ANOVA was carried out including session (first half and second half), distractor eccentricity (central and peripheral), load (1, 2, 4, or 6), and distractor compatibility (incompatible and compatible) as within-subject factors. Mean RTs for each population as a function of distractor eccentricity and load are presented in Table 1, along with the compatibility effects.

A main effect of session indicated that subjects got faster as they became more experienced with the task [835 vs. 791 msec; $F(1,20) = 17.5$, $p < .001$, $MSE = 292,911.9$]. A main effect of load due to slower RTs as load increases confirmed that the task difficulty increases with load [714, 790, 862, and 886 msec; $F(3,60) = 165.1$, $p < .001$, $MSE = 6421.1$]. Finally, a main effect of compatibility established an overall flanker compatibility effect whereby RTs are slower for incompatible than compatible distractors [822 vs. 804 msec; $F(1,20) = 41.6$, $p < .001$, $MSE = 1406.3$]. A significant interaction between load and compatibility replicated Lavie's and others' finding that compatibility effects get smaller as load increases [48, 19, 12, and −6 msec; $F(3,60) = 13.5$, $p < .001$, $MSE = 1604.6$]. Finally, an interaction among session, population, eccentricity, and compatibility indicated different compatibility effects across eccentricities for the two populations in the first and second sessions [$F(1,20) = 4.7$, $p < .041$, $MSE = 589.4$]. This last interaction led us to perform separate analysis for each session.

Analysis of the first session revealed similar main effects and compatibility by load interaction as the omnibus analysis, but importantly no effect was observed with population as a factor (all $ps > .2$); and thus will not be discussed further. In contrast, the second session data revealed several significant population differences.

In the second session, there were main effects of load [$F(3,60) = 129.1$, $p < .001$, $MSE = 3919.8$] and compatibility [$F(1,20) = 27.3$, $p < .001$, $MSE = 1157.7$], as well as a significant interaction between load and compatibility [$F(3,60) = 9.2$, $p < .001$, $MSE = 970.0$] as in the omnibus analysis. More importantly, as predicted, a Population × Eccentricity × Compatibility interaction indicated a larger compatibility effect in the deaf than in the hearing for peripheral distractors, but the opposite trend for central distractors [$F(1,20) = 11.0$, $p < .003$, $MSE = 495.9$]. This effect is depicted in Figure 2. Finally, a Population × Load × Eccentricity interaction suggested different sensitivities to load across eccentricities in the two populations [$F(3,60) = 2.79$, $p < .048$, $MSE = 960.1$]. A similar analysis performed on percentage of error confirmed that these effects are not due to different time–accuracy trade-offs in the two populations. Indeed, the only significant effect with population as a factor was an interaction between population and load [$F(3,60) = 3.7$, $p < .016$, $MSE = 0.0057$] due to a lesser decrement in performance in deaf participants as load
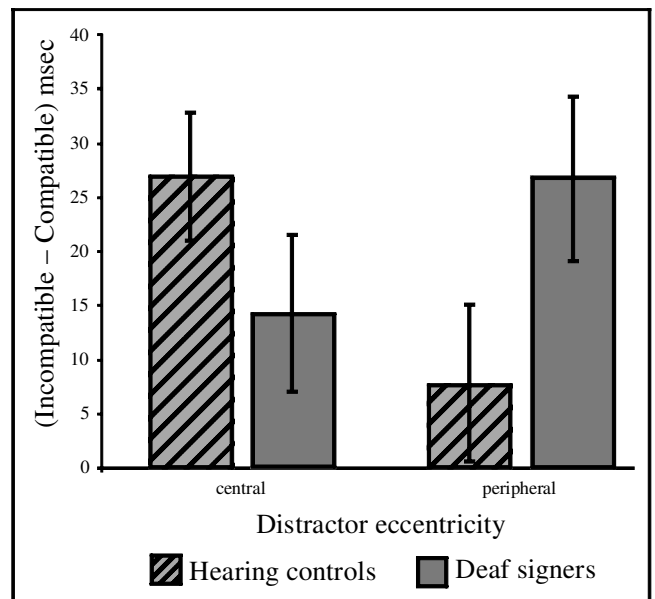

Figure 2. Compatibility effects (msec) for hearing controls and deaf individuals as a function of the distractor eccentricity in Experiment 1. The compatibility effect was measured by the RT difference between displays in which target and distractor were incompatible and those in which they were compatible. For central distractors, hearing displayed a trend for larger compatibility effects than deaf individuals, whereas the opposite effect was observed for peripheral distractors.

increased. All other effects with population, including those with compatibility and eccentricity, were nonsignificant (all $ps > .18$).

The finding of different compatibility effects for central and peripheral distractors in the two populations led us to analyze separately the data for each eccentricity. At each eccentricity, as in the previous analyses, there were main effects of load [central: $F(3,60) = 103.8$, $p < .001$, $MSE = 2397.3$; peripheral: $F(3,60) = 103.7$, $p < .001$, $MSE = 2482.6$], compatibility [central: $F(1,20) = 33.3$, $p < .001$, $MSE = 602.5$; peripheral: $F(1,20) = 11.4$, $p < .003$, $MSE = 1051.0$], as well as an interaction between load and compatibility [central: $F(3,60) = 2.9$, $p < .042$, $MSE = 913.0$; peripheral: $F(3,60) = 7.40$, $p < .001$, $MSE = 982.2$]. Of particular interest to our study was the interaction between population and compatibility corresponding to the within-eccentricity interactions depicted in Figure 2. At each eccentricity, a trend for a population by compatibility interaction was observed though significance was not reached [central: $F(1,20) = 2.94$, $p = .102$, $MSE = 602.5$; peripheral: $F(1,20) = 3.73$, $p = .068$, $MSE = 1051.0$]. The lack of significance in these analyses may be due to the expected loss of power when combining the four different perceptual loads. Indeed, as discussed above, several loads were used in this experiment in order to find the critical loads at which the two populations differ in their attentional resources.

To determine the critical loads, we performed separate ANOVAs for each load with population, eccentricity,

Figure 3. Compatibility effects (msec) as a function of load for hearing controls and deaf individuals for central distractors (A) and for peripheral distractors (B) in Experiment 1. As expected, compatibility effects are marked at low load and decrease as load increases. Population differences are only obtained at the load levels in which attention has been exhausted in one population, but not the other.
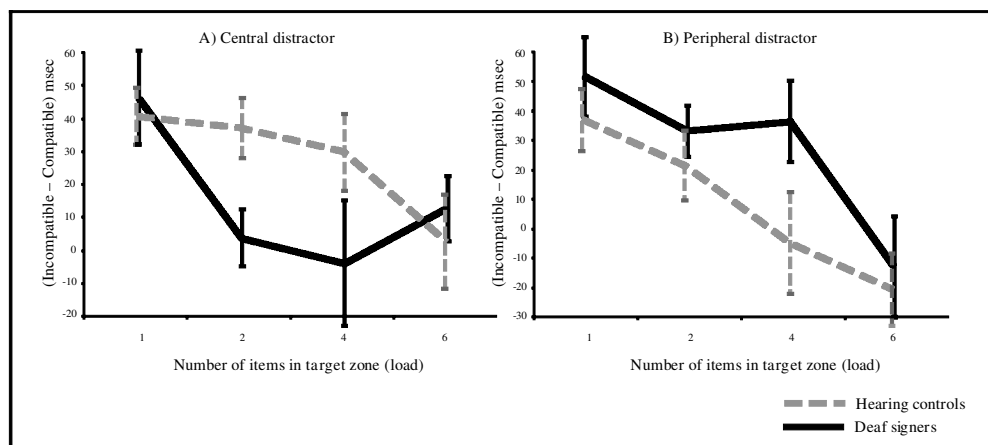
and compatibility as factors. A Population × Eccentricity × Compatibility interaction was found for loads of 2 [$F(1,20) = 8.23, p < .009, MSE = 339.3$] and 4 [$F(1,20) = 6.48, p < .019, MSE = 1178.9$], but not for the extreme loads of 1 [$F(1,20) = 0.145, p > .71, MSE = 770.1$] and 6 [$F(1,20) = 0.007, p > .933, MSE = 983.2$]. The interactions at loads 2 and 4 are similar to that depicted in Figure 2, and in fact are the likely source of that overall interaction. At these loads, hearing individuals begin to exhaust their peripheral resources whereas deaf individuals still have a surplus, with the opposite pattern for central resources. To investigate the population effect within each eccentricity, separate analyses were performed for the central and peripheral conditions at loads of 2 and 4.

For the central condition, a significant population by compatibility interaction was found at a load of 2 [$F(1,20) = 6.6, p < .018, MSE = 454.9$] along with a similar nonsignificant trend at a load of 4 [$F(1,20) = 2.4, p < .133, MSE = 1275.0$]. Both of these effects were due to an increased compatibility effect in the hearing compared with the deaf population (Figure 3A). Such a result supports the hypothesis that hearing have greater attentional resources than deaf individuals in central vision. Specifically, this result suggests that, at a load of 2, hearing subjects still have attentional resources allocated to the center field, whereas deaf individuals have exhausted all of their central resources.

For the peripheral case, a population and compatibility interaction trend was found at a load of 4 [$F(1,20) = 3.192, p < .089, MSE = 1434.7$]. This trend was toward a greater compatibility effect in the deaf population (Figure 3B). While this effect did not reach significance, inspection of the distribution of subjects revealed an outlier in the deaf population. This participant had a compatibility effect 2.5 standard deviations away from the deaf population's mean (though within the range of the hearing population). While we can offer no valid explanation for this outlier, when the data are considered without this participant there is a significant population by compatibility interaction [$F(1,19) =$

6.47, $p < .02, MSE = 1138.0$] at a load of 4. No trend was found at a load of 2, suggesting that both populations had a surplus of peripheral resources at that load. Thus in the case of peripheral distractors, it appears that at a load of 4 deaf subjects still have attentional resources allocated to the peripheral field, whereas hearing have exhausted their peripheral resources. Together, these results support the hypothesis that deaf individuals have greater attentional resources in the peripheral visual field, and indicate that hearing have greater attentional resources in the central visual field.

Discussion

A summary of the results can be seen in Figure 3A and B, which plot the compatibility effect for central and peripheral distractors, respectively, as a function of load for each population. In this figure, positive values (compatibility effect) reflect excess resources available to that subject population. With a load of 1, each population has a surplus of resources available to automatically process the distractor and produce a compatibility effect. As load is increased, the two populations separate by the magnitude of attentional resources at the two eccentricities, as indexed by the compatibility effect. When resources are exhausted, the compatibility effect disappears, as the participants must call upon all of their attentional resources to find the target and successfully ignore the distractor. In the central distractor condition (Figure 3A), as load increases, the deaf population exhaust their central resources at a lower load than the hearing population. In the peripheral condition (Figure 3B), the hearing population exhaust their peripheral resources at a lower load than the deaf population.

These findings establish that not only do deaf garner more attentional resources in the periphery, but that this seems to bring with it reduced resources at the center of the visual field. As we suggested earlier, it might be the case that the expanded resources in the periphery are drawing away resources that would normally be used for central attention. However, at this

point, it is unclear whether these differences are really linked or the result of two distinct mechanisms.

Although we have proposed that deafness leads to the observed reorganization of the allocation of attention over the visual field, an alternative explanation is that this change is brought about by the experience of deaf subjects with American Sign Language (ASL). ASL was the primary mode of communication among the deaf studied in Experiment 1. Typically, during signing exchanges, the signee fixates the face of the signer and monitors the hand shapes and hands motions of the signer in the peripheral field. A recent study indicates that ASL signs fall at an eccentricity of about 7° on each side of fixation (Bosworth, Wright, Bartlett, Corina, & Dobkins, 2000). Thus, it is possible that the reliance of ASL on peripheral processing, rather than deafness per se, led to the reallocation of visual attention resources toward the periphery. To assess the impact of early signing, hearing individuals born to deaf parents and exposed to ASL from birth were tested on the same paradigm as in Experiment 1. If the different distribution of attentional resources is due to sign language exposure, the hearing signers should show greater peripheral attention resources than the hearing controls in line with the deaf participants. However, if the native signers show a pattern similar to that of hearing controls, it will suggest that the peripheral enhancement of attention in deaf signers is a byproduct of the early loss of auditory input.

EXPERIMENT 2

As stated above, the goal of Experiment 2 was to assess the impact of early signing on the distribution of attention. Experiment 2 was identical to Experiment 1 except that subjects were hearing individuals that were raised from birth in a signing environment. Like the deaf participants included in Experiment 1, the hearing sign-

ers had all been exposed to sign before the age of three, and were all using signing on a daily basis.

Results

Table 2 displays the compatibility effects at each load and eccentricity for hearing signers. The performance of the hearing signers was first compared to that of hearing controls to test for a peripheral enhancement due to signing.

Hearing Signers versus Hearing Controls

The omnibus ANOVA on RTs revealed a main effect of population due to slower RTs in the hearing native signers than in the hearing controls [$F(1,16) = 6.9, p < .018, MSE = 290,450.5$]. As in Experiment 1, there was a main effect of load [$F(1,16) = 127.6, p < .0001, MSE = 7986.4$], compatibility [$F(1,16) = 33.9, p < .0001, MSE = 1305.2$], as well as an interaction between these two factors [$F(3,48) = 6.5, p < .001, MSE = 1656.1$]. Importantly, a main effect of session indicated a practice effect across session [$F(1,16) = 13.0, p < .002, MSE = 20,267.7$] and interactions among session, eccentricity, and compatibility [$F(1,16) = 4.7, p < .045, MSE = 688.9$], as well as among session, population, load, eccentricity, and compatibility suggested different pattern of compatibility across the two sessions [$F(3,48) = 2.8, p < .047, MSE = 876.4$]. Thus, as in Experiment 1, the two sessions were analyzed separately. The analysis of the first session revealed a main population effect [$F(1,16) = 6.0, p < .026, MSE = 155,131.1$], but no other effect with population (all other $ps > .13$), and will not be discussed further.

In the second session, there were main effects of load [$F(3,48) = 93.2, p < .001, MSE = 5036.3$] and of compatibility [$F(1,16) = 17.9, p < .001, MSE = 864.1$], as well as a significant interaction between load and compatibility [$F(3,48) = 4.3, p < .009, MSE = 1386.3$]. These effects

Table 2. Mean RTs (Milliseconds) and Compatibility Effect (Mean ± Standard Error) at Each Load for Hearing Native Signers

	Load 1	Load 2	Load 4	Load 6
Central distractor				
Incompatible	808.8 ± 49.4 (5.6)	877.4 ± 50.0 (4.2)	966.6 ± 56.0 (19.5)	947.7 ± 55.7 (25.0)
Compatible	772.9 ± 45.8 (2.1)	866.2 ± 65.4 (4.9)	947.6 ± 54.0 (12.5)	955.9 ± 34.7 (19.5)
Compatibility effect	35.9 ± 14.9 (3.5)	11.2 ± 24.3 (−0.7)	19.0 ± 13.9 (7.0)	−8.2 ± 24.0 (5.5)
Peripheral distractor				
Incompatible	795.4 ± 44.1 (4.9)	874.9 ± 40.2 (8.4)	936.7 ± 51.7 (16.0)	982.5 ± 64.8 (19.6)
Compatible	772.7 ± 45.9 (3.5)	862.5 ± 49.2 (6.3)	967.4 ± 57.1 (12.5)	973.4 ± 59.4 (20.9)
Compatibility effect	22.7 ± 8.5 (1.4)	12.4 ± 23.0 (2.1)	−30.7 ± 22.1 (3.5)	9.1 ± 29.6 (−1.3)

The percentage of error is given in parenthesis for each condition.
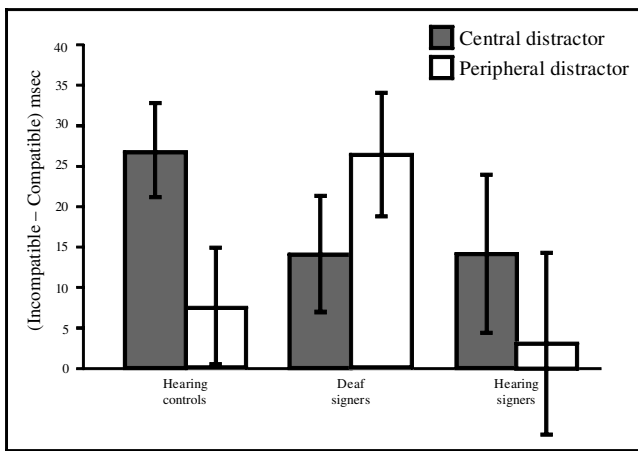
Figure 4. Compatibility effects (msec) as a function of distractor eccentricity for hearing controls, deaf signers and hearing signers (from Experiments 1 and 2). As for hearing controls, hearing native signers tended to show greater effects from central than peripheral distractors.

were similar to those reported in Experiment 1. Unlike in Experiment 1, a main effect of population was present in which native signers were slower overall to respond than hearing [894 vs. 765 msec; $F(1,16) = 6.9$, $p < .018$, $MSE = 155,587.1$]. The only other significant effect was an interaction between eccentricity and compatibility indicating greater compatibility effects for the central condition than for the peripheral condition [$F(1,16) = 6.9$, $p < .018$, $MSE = 706.5$]. Combined with the lack of any other interactions involving population (all $ps > .2$), these results suggest that central distractors are more distracting than peripheral ones in hearing controls and in hearing signers (Figure 4). A similar lack of population effect was observed in the analysis of the error data. All effects with population as a factor were nonsignificant (all $ps > .07$).

Distribution differences between these two populations may have been missed, however, because of a lack of power, as the sample of hearing signers was small. Since analyzing all loads at once also diminishes the power of our analysis, the data were further separated by load. The main effect of population on RTs was found at each load [load 1: $F(1,16) = 7.5$, $p < .014$, $MSE = 31,947.9$; load 2: $F(1,16) = 7.3$, $p < .015$, $MSE = 38,406.3$; load 4: $F(1,16) = 5.4$, $p < .033$, $MSE = 52,528.5$; load 6: $F(1,16) = 5.5$, $p < .032$, $MSE = 47,813.2$], but there were no interaction involving population at any load (all $ps > .24$). Failure to get any population interaction, even at this level, prompted the end of further analysis. No significant difference was found between the hearing signers and hearing controls other than the main effect of an overall increase in RT for the hearing signers.

Hearing Signers versus Deaf Signers

The omnibus ANOVA on RTs including session, population, eccentricity, load, and compatibility as factors re-

vealed main effects of session [$F(1,14) = 13.0$, $p < .003$, $MSE = 15,339.7$], load [$F(3,42) = 182.3$, $p < .001$, $MSE = 4479.7$], and of compatibility [$F(1,14) = 46.5$, $p < .001$, $MSE = 994.0$], as well as a load by compatibility interaction [$F(3,42) = 4.9$, $p < .005$, $MSE = 2023.9$]. As discussed previously, these effects, respectively, indicate a practice effect across session, an increase in task difficulty as load increases, an overall compatibility effect due to slower RTs in the incompatible condition, and importantly, smaller compatibility effects as load increases in accordance with the proposal of Lavie and colleagues. A Population × Load × Eccentricity interaction was also present [$F(3,42) = 3.1$, $p < .034$, $MSE = 1538.2$], along with an interaction among session, population, load, eccentricity, and compatibility [$F(3,42) = 4.4$, $p < .008$, $MSE = 735.6$]. This last interaction prompted the separation of the data by session. As in all the analyses performed, the first session revealed no significant population difference, and will not be discussed further (all $ps > .15$; except for a marginally significant Population × Load interaction, $p = .055$).

In the second session there were main effects of load [$F(3,42) = 126.2$, $p < .001$, $MSE = 2896.8$] and compatibility [$F(1,14) = 14.2$, $p < .002$, $MSE = 1188.1$], as well as an interaction between them [$F(3,42) = 3.7$, $p < .018$, $MSE = 1388.1$], indicating the expected reduction of the compatibility effect as load increases. More importantly for our purpose, a Population × Load × Eccentricity × Compatibility interaction suggested different compatibility effects in hearing signers and deaf signers as a function of load and compatibility [$F(3,42) = 3.3$, $p < .027$, $MSE = 825.4$]. The interaction was further examined by analyzing each load separately. Before turning to these analyses, it is worth noting that the ANOVA with population, load, eccentricity, and compatibility as factors performed on the percentage of error did not reveal any effect with population (all $ps > .2$), ruling out the possibility of time–accuracy trade-offs in the effects observed with RTs.

Analyses of loads 1, 2, and 6 revealed no effect (all $ps > .21$) and will not be discussed further. At load 4, an interaction among population, eccentricity, and compatibility indicated different compatibility effects as a function of eccentricity in hearing signers and deaf signers [$F(1,14) = 8.3$, $p < .012$, $MSE = 915.1$]. This effect mirrors that seen in Experiment 1 between hearing controls and deaf signers. Peripheral distractors led to a greater compatibility effect than central distractors in deaf signers, whereas the opposite pattern was observed for hearing signers. Separate analyses for central and peripheral distractors at load 4 revealed no significant effect for the central condition (all $ps > .2$), but a significant interaction between population and compatibility for peripheral distractors [$F(1,14) = 7.3$, $p < .017$, $MSE = 1147.8$]. This last effect establishes that peripheral distractors are more distracting to deaf signers than hearing signers and

suggests greater attentional resources in the periphery for deaf signers than for hearing signers.

Combined with the finding that hearing signers and hearing controls displayed similar compatibility effects across eccentricities, this latter observation led us to use contrast analysis to test the proposal that the shift in attentional resources toward the periphery is specific to deaf signers (Figure 4). In accordance with this hypothesis, a contrast analysis was performed on the difference between the compatibility effect for central distractor and that for peripheral distractor assigning weights of -2 to the deaf group and of $+1$ to each of the hearing groups. The contrast effect was significant supporting the view that greater compatibility effects from peripheral than central distractors are specific to the deaf population [$F(1,25) = 7.3$, $p < .012$, $MSE = 413.5$]. The relative contribution of the central and peripheral conditions to this latter finding was then characterized by carrying out separate contrast analyses on the size of the compatibility effect for central distractors and on that for peripheral distractors. In the central condition, the contrast was not significant ($p > .37$); but it was robust in the peripheral condition [$F(1,25) = 5.0$, $p < .035$, $MSE = 350.7$]. This finding confirms that the deaf population is unique in their surplus of resources in the periphery.

Discussion

Experiment 2 tested the effects of central and peripheral distractors in hearing signers to determine the role of signing in the enhanced attentional resources toward the periphery observed in deaf signers in Experiment 1. The results establish that hearing signers display a similar central attention bias as hearing controls, and like hearing controls, appear to have less attentional resources over the periphery than deaf signers (Figure 4). Thus, the population effects observed in Experiment 1 cannot be attributed solely to an extensive practice with signing. Rather, they appear to be a reflection of plastic changes due to early deafness. While sign language exposure may be a contributing factor to peripheral enhancement in the deaf, this experience is not enough to lead to changes in hearing individuals. This observation is noteworthy as it suggests boundary conditions on plasticity. Indeed, it appears that not all early experience that requires monitoring of the visual periphery leads to an enhancement of attentional resources toward the periphery. The lack of a peripheral enhancement in hearing signers is surprising when one considers the extensive peripheral processing signing requires. Furthermore, it is unlikely that this lack of effect is due to the eccentricity tested, as $4.2°$ is well within the $7°$ of eccentricity ASL signs fall into (Bosworth et al., 2000).

The observation that peripheral visual attention is enhanced in deaf signers but not in hearing signers is also supported by two other studies in the literature. In a seminal article on the topic, Neville and Lawson (1987c) compared evoked potentials in hearing controls, deaf signers, and hearing signers as they were asked to detect the direction of motion of a small square either in peripheral vision (approximately $17°$) or in central vision. During the peripheral condition, deaf signers displayed evoked potentials over occipital and temporal sites that were several times the magnitude of those observed in hearing controls and in hearing signers. This effect was specific to the peripheral condition, as no group differences were observed for the central condition (Neville & Lawson, 1987a, 1987b, 1987c). Along the same lines, Bavelier et al. (2001) have found that when asked to report changes in moving stimuli that could occur either peripherally ($8°$) or centrally, deaf individuals displayed a bias for better performance in the peripheral field, whereas hearing controls and hearing signers displayed a bias for better performance in the central field. Additionally, using functional magnetic resonance imaging, this study tracked the level of activation of the motion area MT/MST as attention was distributed either centrally or peripherally. Recruitment of MT/MST was enhanced in the peripheral attention condition in deaf signers but not in hearing controls or hearing signers (Bavelier et al., 2001). Taken together, these results suggests that the enhancement of peripheral attention in deaf signers is brought about by early deafness rather than signing.

Although the observation that visual attention to the periphery is enhanced in deaf signers is in line with a few recent studies, it stands as a surprise when compared to the host of studies reporting either no changes or deficits in visual functions in the deaf population. This discrepancy may be in part attributed to the etiology of the subjects included in the deaf group. Previous studies did not systematically focus on deaf individuals born to deaf parents and may have included subjects with central nervous system damage accounting for the poorer performance of the deaf group. However, it also came to our attention that a number of the studies of visual skills have relied on the use of alphanumeric characters. The use of such materials to test visual skills in the deaf population is problematic as deaf individuals have much less practice with written English than hearing controls or hearing signers. In Experiment 3, we explored the possibility that the use of alphanumeric characters reduces any deaf advantage as hearing individuals benefit from their greater familiarity with these stimuli.

EXPERIMENT 3

Studies investigating visual differences in the deaf have often relied on stimuli composed of alphanumeric characters (Quittner et al., 1994; Reynolds, 1993; Carey & Blake, 1974; Henderson & Henderson, 1973). In some

cases, letters were chosen specifically to investigate linguistic variations. However, in most cases, there is the possibility that linguistic factors may have interfered with the visual differences being investigated. There is indeed ample literature showing that English print is less readily processed in the deaf than in the hearing (Marschark, 1993; Doehring & Rosenstein, 1960). Furthermore, a number of studies suggest that deaf individuals may rely on different mechanisms than hearing individuals to process print. Hemifield studies have revealed different lateralization in the deaf population favoring the right visual cortex for the processing of letters (Ross, 1983; Phippard, 1977). Ross (1983) has suggested that letters are processed based on a configurational rather than a phonological basis in the deaf. Neville et al. (1998) have shown that deaf individuals display a very different pattern of cortical organization from that of hearing individuals when reading English. Additionally, even well-educated deaf college students do not possess reading skills in line with their hearing counterparts. (In our study, deaf college students stated that their ability to read English was good, but not perfect.) This effect is likely to be attributable in part to the fact that written words and letters have auditory associations and phonological representations in the hearing, that are not readily available to the deaf.

There is little doubt that college-educated hearing individuals are more familiar with alphanumeric characters than their deaf counterparts. This is likely to result in a processing advantage for hearing subjects that can contaminate any purely visual effect under study. The goal of Experiment 3 was to directly assess the impact of stimuli choice when comparing visual functions in deaf and hearing individuals. The same subjects as in Experiment 1 returned to participate in a similar study as Experiment 1 except that letters were used instead of shapes. It is worth noting that the population effects seen in Experiment 1 were enhanced with practice, so having done Experiment 1 should benefit any population interactions in Experiment 3.

Results

Overall RTs and compatibility effects are given in Table 3. The omnibus ANOVA on RTs including session, population, eccentricity, load, and compatibility as factors revealed a main population effect [$F(1,20) = 9.72, p < .005$,

Table 3. RTs (Milliseconds) and Compatibility Effect (Mean ± Standard Error) at Each Load for Each Population and Distractor Eccentricity in Experiment 3

Population	Load 1	Load 2	Load 4	Load 6
Central distractor				
Hearing				
Incompatible	664.7 ± 15.6 (8.7)	690.9 ± 16.1 (5.2)	748.1 ± 24.2 (15.7)	793.0 ± 26.3 (21.5)
Compatible	618.4 ± 15.4 (1.9)	656.9 ± 12.5 (5.8)	739.5 ± 19.4 (10.5)	769.4 ± 27.2 (22.4)
Compatibility effect	46.3 ± 11.2 (6.8)	34.0 ± 10.6 (0.6)	8.6 ± 15.9 (5.2)	23.6 ± 12.8 (−0.9)
Deaf				
Incompatible	744.2 ± 29.8 (4.1)	801.9 ± 32.6 (4.8)	862.3 ± 47.1 (6.9)	889.0 ± 42.4 (22.5)
Compatible	700.2 ± 36.9 (1.7)	767.9 ± 38.5 (1.3)	864.3 ± 36.0 (11.0)	886.9 ± 40.4 (22.0)
Compatibility effect	44.0 ± 17.7 (2.4)	34.0 ± 12.1 (3.5)	−2.0 ± 26.1 (−4.1)	2.1 ± 15.0 (0.5)
Peripheral distractor				
Hearing				
Incompatible	637.8 ± 15.9 (4.2)	678.0 ± 18.0 (7.7)	732.6 ± 18.5 (15.3)	758.7 ± 23.9 (23.9)
Compatible	609.9 ± 12.4 (2.1)	649.8 ± 12.5 (4.2)	731.2 ± 18.5 (14.7)	772.7 ± 25.7 (21.9)
Compatibility effect	27.9 ± 8.2 (2.1)	28.2 ± 31.1 (3.5)	1.4 ± 12.2 (0.6)	−14.0 ± 18.0 (2.0)
Deaf				
Incompatible	750.3 ± 35.0 (3.7)	800.7 ± 41.1 (4.6)	856.1 ± 34.6 (13.5)	904.8 ± 39.8 (23.5)
Compatible	685.8 ± 27.9 (3.8)	747.4 ± 32.4 (5.3)	865.6 ± 41.6 (10.1)	899.9 ± 44.2 (18.3)
Compatibility effect	64.5 ± 12.5 (−0.1)	53.3 ± 20.1 (−1.3)	−9.5 ± 16.5 (3.4)	4.8 ± 14.0 (5.2)

The percentage of error is given in parenthesis for each condition.
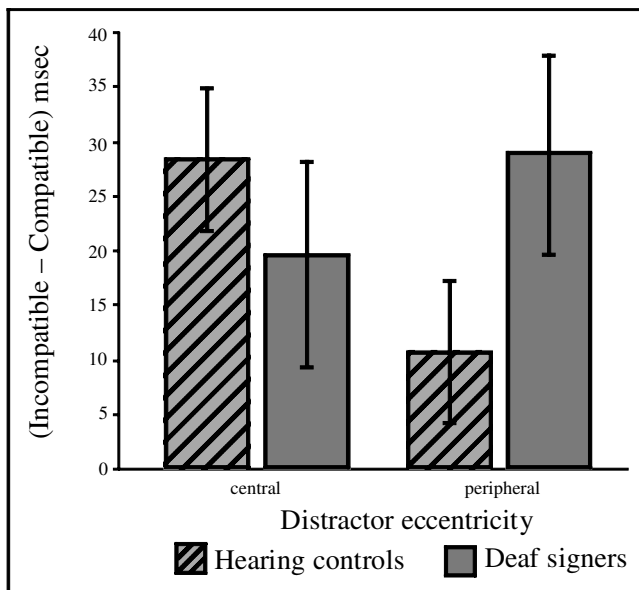
Figure 5. Compatibility effects (msec) for hearing controls and deaf individuals as a function of the distractor eccentricity when letters were used as stimuli (Experiment 3). Although not significant, the same trend as in Experiment 1 was observed of greater compatibility effect from central distractors in hearing controls than deaf individuals and the opposite trend from peripheral distractors.

$MSE = 231,433.6$]. As expected, deaf individuals were significantly slower than their hearing counterparts when using letters (825 vs. 711 msec) confirming that they process letters less readily than their hearing counterparts. Otherwise, similar effects as those described for shapes were observed. In particular, there were main effects of session [$F(1,20) = 12.10$, $p < .002$, $MSE = 5199.3$], load [$F(3,60) = 230.5$, $p < .001$, $MSE = 3802.9$], and of compatibility [$F(1,20) = 55.45$, $p < .001$, $MSE = 1335.6$], as well as a load by compatibility interaction [$F(3,60) = 14.37$, $p < .001$, $MSE = 1289.7$]. As when shapes were used, these indicate, respectively, a practice effect across session (772 msec in the first session vs. 753 msec in the second session), an increase in task difficulty as load increases (680, 731, 802, and 838 msec for loads 1

through 6, respectively), an overall compatibility effect due to slower RTs for the incompatible condition than for the compatible condition (773 vs. 752 msec), and importantly, smaller compatibility effects as load increases in accordance with the proposal of Lavie and colleagues (42, 34, 5, and 2 msec for loads 1 through 6, respectively). Finally, a Session × Population × Eccentricity interaction [$F(1,20) = 4.6$, $p < .044$, $MSE = 731.2$] indicated different compatibility effects across sessions in the two populations and led us to analyze the two sessions separately. As in all the analyses performed, the first session revealed no significant population difference and will not be discussed further (all $ps > .2$).

In the second session, as observed in the omnibus analysis, there were main effects of population [$F(1,20) = 8.77$, $p < .008$, $MSE = 122,581.1$], load [$F(3,60) = 184.09$, $p < .001$, $MSE = 2402.2$], and compatibility [$F(1,20) = 39.87$, $p < .001$, $MSE = 1021.3$], as well as an interaction between load and compatibility [$F(3,60) = 9.32$, $p < .001$, $MSE = 1211.0$]. There were no other significant effects. However, a nonsignificant trend in the interaction among population, eccentricity, and compatibility [$F(1,20) = 3.253$, $p < .086$, $MSE = 1135.3$] suggested a similar tendency as in Experiment 1 for different compatibility effects across eccentricities in the two populations (Figure 5). This effect was confirmed by the analysis of error data. In addition to robust load [$F(3,60) = 90.3$, $p < .0001$, $MSE = 0.0069$] and compatibility [$F(1,20) = 8.5$, $p < .008$, $MSE = 0.0069$] effects, an interaction among population, load, eccentricity, and compatibility [$F(3,60) = 2.9$, $p < .04$, $MSE = 0.0032$] indicated different compatibility effects across load and eccentricity in the two populations.

To draw comparisons with Experiment 1, a similar breakdown by load and eccentricity was performed for RT and error analysis. These data are summarized in Figure 6A and B for RTs. For central distractors, none of the load revealed a significant interaction between population and compatibility in RTs analyses (all $ps > .28$). However, a significant interaction between population and compatibility was observed at load of 4 in error data

Figure 6. Compatibility effects (msec) as a function of load for hearing controls and deaf individuals for central distractors (A) and for peripheral distractors (B) when letters were used as stimuli (Experiment 3).
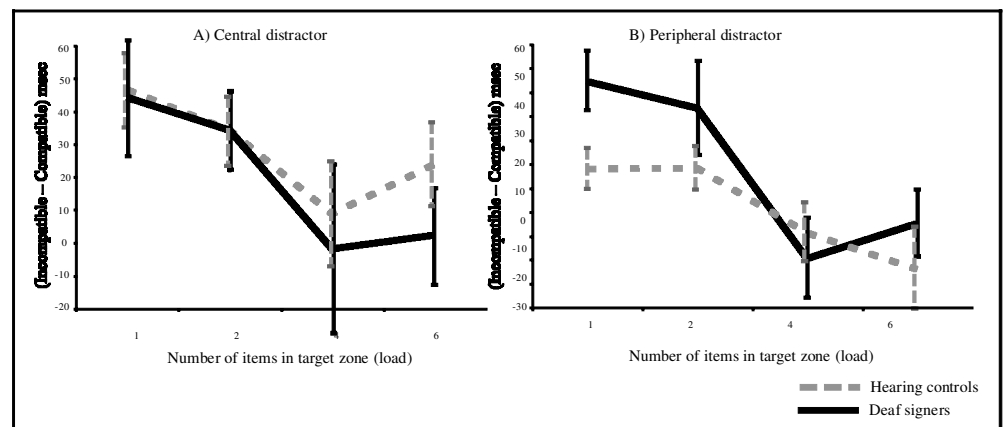
[$F(1,20) = 10.3$, $p < .004$, $MSE = 0.0023$, all other load ps $> .055$], indicating a larger compatibility effect in hearing than in deaf participants. For peripheral distractors, a population by compatibility interaction was present at a load of 1 for RTs analysis [$F(1,20) = 6.284$, $p < .021$, $MSE = 579.5$, all other load ps $> .24$]. As illustrated in Figure 6B, the deaf population displayed a greater compatibility effect than the hearing population in this condition. No effect was observed in the error analysis (all ps $> .2$).

Discussion

Experiment 3 confirms that alphanumeric stimuli are less readily processed in deaf individuals than in hearing individuals. The deaf were slower than the hearing by approximately 100 msec. This difference in RTs is likely a reflection of a difference in the automaticity of letter recognition in the two populations. Because the compatibility effect under study relies in part on the automatic processing of distracting information, the use of stimuli that are not matched in their ease of processing in the two populations is likely to introduce a confound when comparing population performance. Accordingly, the use of alphanumeric characters led to a reduction in the population differences in terms of the compatibility measure. It is, however, worth noting that even in these conditions, the deaf maintained a peripheral advantage and the hearing a central advantage. To summarize, Experiment 3 demonstrates the influence that variations in the stimuli can have and supports the contention that nonlinguistic stimuli should be used when investigating visual skills in the deaf population; in addition, its result reinforces the proposal of different spatial distribution of attention in deaf and hearing participants.

GENERAL DISCUSSION

Our results demonstrate that the spatial distribution of visual attention differ in the deaf population and in hearing controls. Experiment 1 establishes an opposite effect of peripheral and central distractors in deaf and hearing participants. Peripheral distractors were more distracting to deaf individuals, but central ones were more distracting to hearing individuals. This pattern of results supports the proposal of a shift of attentional resources from the center to the periphery in the deaf participants. This finding is in line with the few previous reports of enhancements of peripheral vision in the deaf (Bavelier et al., 2001; Reynolds, 1993; Loke & Song, 1991; Neville & Lawson, 1987b) and further specifies a source of these enhancements at the attentional level. Experiment 2 rules out the sufficiency of early exposure to a visuospatial language as an explanation for the redistribution of spatial attention observed in deaf participants. Hearing individuals, born within the deaf

community and exposed to ASL from birth, showed the same greater distractor effect from central than peripheral distractors as that observed in hearing controls (Figure 4). The two other studies that have tested the impact of early exposure to sign language on peripheral processing are in accordance with this finding. Neville and Lawson (1987c) reported enhanced neural responses as measured by ERP to moving stimuli in the periphery in the deaf population but not in hearing controls or hearing native signers. More recently, Bavelier et al. (2001) also distinguished the deaf from both the hearing controls and the hearing signer populations in an fMRI study focusing on MT/MST activation to attended peripheral visual field motion. These findings establish that early exposure to sign language is not sufficient to lead to the peripheral shift of attentional resources observed in congenitally deaf individuals. Although early exposure to sign language may work in synergy with early deafness to lead to the peripheral enhancement noted in deaf signers, the data available establish that early deafness on its own is a necessary condition for this enhancement. Finally, Experiment 3 stresses the importance of avoiding the use of alphanumeric characters when testing visual skills in the deaf population. Although a similar trend as in Experiment 1 for a greater effect from peripheral distractor in the deaf participants was noted, the overall population difference was much weaker than in Experiment 1 in which geometrical shapes were used. Hence, the greater processing advantage alphanumeric characters afford in the hearing population is likely to muddy the purely visual mechanisms under study.

This study establishes a redistribution of visual attention resources toward the periphery in deaf individuals. This finding is consistent with reports that deaf individuals outperform hearing controls during visual search tasks (Rettenbach et al., 1999; Stivalet et al., 1998; Marendaz, Robert, & Bonthoux, 1997). Indeed, in a recent study on the role of practice in visual search tasks in hearing individuals, Sireteanu and Rettenbach (2000) have linked the ability for searches to be efficient with the capacity to distribute one's attention more effectively to peripheral locations in the search display. It is worth noting that although deaf individuals have not always been observed to be better at detecting targets during visual search tasks, they have consistently shown an enhanced capacity at terminating searches when no target was presented. Similarly, the effects of practice on visual search tasks studied by Sireteanu and Rettenbach are specifically marked for the no target condition. In their study, the enhanced performance that resulted from practice was not specific to the trained visual search task, but generalized to other visual search tasks, consistent with the proposal that the learning occurs at a rather high level of visual processing, such as visual attention. Although this result may lead one to conclude that a redistribution of attentional

resources toward the periphery can be easily achieved through training with any task that requires peripheral processing, our results indicate boundary conditions on this effect. The lack of peripheral enhancement in hearing native signers whose daily use of ASL requires monitoring of the visual periphery indicates that not all visual tasks that require peripheral monitoring lead to a redistribution of attention toward the periphery. Additionally, no such effect is observed in deaf children even though, as in deaf adults, they can only rely on processing of the visual periphery to monitor their peripersonal space. For example, using similar visual search tasks as those used in adults, Rettenbach et al. (1999) observed that deaf children and adolescents systematically under-performed their matched hearing controls. This suggests that the change in the spatial distribution of attention observed in the deaf population emerges through a slow maturing process and may not rely on the same learning mechanisms and/or brain reorganization as those modified by practice in hearing subjects.

This work implies that the spatial distribution of visual attention is biased toward the peripheral field after early auditory deprivation. A recent study of congenitally blind individuals suggests a parallel pattern for the spatial distribution of auditory attention. Roder et al. (Roder et al., 1999; Teder-Salejarvi, Hillyard, Roder, & Neville, 1999) have reported improved spatial resolution for peripheral sound sources in congenitally blind individuals. Evoked potentials recorded at the same time revealed sharper tuning of early spatial attention mechanisms in the blind participants over parieto-temporal sites. Electrophysiological responses over temporo-parietal sites have also been found to be enhanced in the congenitally deaf during peripheral visual processing (Neville & Lawson, 1987c). Recently, the use of fMRI has allowed us to implicate the posterior parietal cortex as one of the areas mediating the enhancement of peripheral processing in the deaf (Bavelier et al., 2000). These results converge to indicate that early sensory deprivation, such as blindness or deafness, leads to a reorganization of spatial attention, which is at least in part mediated by a reorganization of the posterior parietal cortex, one of the main centers of spatial attention.

METHODS

Participants

Hearing and deaf participants were recruited from the student body of the University of Rochester and the National Technical Institute of the Deaf (NTID), respectively. Criteria for inclusion of deaf subjects were congenital hearing loss of 85 dB or more, exposure to sign language no later than age 3, and at least one deaf parent. None of the participants reported a history of neurological problem. Eighteen deaf participants were initially tested, but some had to be excluded later by not satisfying these requirements (six with initial sign language exposure after age 3 and one with less than 85-dB hearing loss). All subjects were required to have normal or corrected-to-normal vision as tested by the Snellen eye chart test. This criteria lead to the exclusion of one deaf participant. Thus, the study included 12 hearing students (8 women and 4 men; mean age = 21 years old) and 10 deaf students (6 women and 4 men; mean age = 21.2 years old).

The third population tested was composed of six hearing young adults, born to deaf parents, and raised in a signing community (4 women and 2 men; mean age = 22.2). Criteria for inclusion included normal hearing, at least one deaf parent, excellent ASL skills initiated prior to age 3, and daily use of ASL, in addition to normal or corrected-to-normal vision and no history of significant neurological problems. All subjects had strong ties to the deaf community; five of them were students and one was an interpreter for the deaf.

All participants were paid for their participation and provided informed consent in accordance with the guidelines set by the University of Rochester and NTID.

Stimuli

Stimuli were presented on a 21-in. Mitsubishi monitor from a standard PC equipped with a Matrox Millenium video card using OpenGL routines. Subjects were seated with their eyes 60 cm from the monitor in a darkened room. The stimuli included three categories of items (target, filler, and distractor) presented in light gray on a black background.

In Experiment 1, the items were all filled shapes. The target set consisted of a square and a diamond, the filler set of a house-like shape, an upside-down house-like shape, a sideways trapezoid, a triangle pointing up, and a triangle pointing down, and the distractor set of a square, a diamond, and an elongated circle (Figure 1). Target shapes and filler shapes subtended an average of 0.6° vertically and 0.4° horizontally and were always presented inside circular frames as illustrated in Figure 1. Throughout the experiment, the six circular frames were presented at the same location arranged around the central fixation point at a distance of 2.1°. The distance between the center of adjacent frames was 2.1°. The frames in which target and fillers appeared were randomly selected across trials.

Distractor shapes included shapes from the target set as well as a neutral distractor (elongated circle). The distractor was positioned either centrally (0.5° from fixation) or peripherally (4.2° from fixation) from the target ring (2.1° from fixation). Although this eccentricity does not qualify as peripheral vision, this layout was chosen to ensure that peripheral and central distractors were at a comparable distance from the target ring. This point is important if differences in effects between

central and peripheral distractors are to be interpreted in terms of eccentricity rather than in terms of absolute distance. The size of the distractor was corrected for the known cortical magnification factor (Rovamo & Virsu, 1979). Accordingly, central distractors subtended 0.3° vertically and 0.2° horizontally and peripheral distractors subtended 0.9° vertically and 0.5° horizontally. The peripheral distractor was always presented outside of the ring, 4.2° from the center either to the left or to the right. The central distractor was always inside the ring, 0.5° from the center either to the left or to the right.

The only modification in Experiment 3 consisted in the use of letters in place of shapes. The target letters were ''N'' and ''X,'' filler letters consisted of the letters ''Z,'' ''V,'' ''W,'' ''H,'' and ''K,'' and distractor letters consisted of ''N,'' ''X,'' and ''O'' (''O'' acting as a neutral distractor).

Procedure

Each trial began with a 1-sec fixation point followed by a 100-msec presentation of the trial shapes. The task of the participants was to identify a target object (Experiments 1 and 2: either a square or a diamond; Experiment 3: either the letter ''N'' or the letter ''X'') in the ring of circles. Participants responded to the stimuli by pressing the corresponding key with labels representing the two possible target shapes. Feedback was given by way of a change in color of the fixation point. Trials were grouped into two sessions of 12 blocks comprised of 48 trials each (576 trials per session). After each block, participants were given a resting screen that informed them of their performance (RT and percentage of correct). Participants initially viewed the stimuli passively until they felt comfortable making a response (usually 5–15 trials). Responses were monitored for two blocks of 48 trials to assure comprehension of the task. Following successful training, the participants were then left alone to complete the first session. This was followed by an intermission and refreshment break. Then, the second session was initiated. The entire experiment lasted approximately 1.5 hr.

Data Analysis

Both RT and error analyses were performed using ANOVA. For RT analysis, the RT data were filtered to remove any outliers. This was accomplished by first removing any RTs greater than 1800 msec and less than 300 msec. Trials were then separated based on distractor eccentricity (central and peripheral). For each subject, a mean and standard deviation was computed. Any trials with RTs greater than 2 standard deviations from the mean were removed. These filtered data were then entered into ANOVAs with RTs as the dependent variable, with session, eccentricity, load, and compatibility as within-subject factors, and population as a between-subjects factor. The compatibility effect was measured by comparing compatible and incompatible trials. Error analysis displayed few significant effects and none that were indicative of time–accuracy trade-off. For this reason, they are only briefly mentioned in the Results section.

REFERENCES

Bavelier, D., Brozinsky, C., Tomann, A., Mitchell, T., Neville, H., & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neuroscience, 21,* 8931–8942.

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T. V., Corina, D. P., Liu, G., & Neville, H. J. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience, 20,* 1–6.

Bosworth, R., & Dobkins, K. (1999). Left hemisphere dominance for motion processing in deaf signers. *Psychological Science, 10,* 256–262.

Bosworth, R. G., Wright, C. E., Bartlett, M. S., Corina, D. P., & Dobkins, K. R. (2000). *Characterization of the visual properties of signs in ASL.* Paper presented at the Theoretical Issues in Sign Language Research, Amsterdam.

Bross, M. (1979). Residual sensory capacities of the deaf: A signal detection analysis of a visual discrimination task. *Perceptual and Motor Skills, 48,* 187–194.

Bross, M., & Sauerwein, H. (1980). Signal detection analysis of visual flicker in deaf and hearing individuals. *Perceptual and Motor Skills, 51,* 839–843.

Carey, P., & Blake, J. (1974). Visual short-term memory in the hearing and the deaf. *Canadian Journal of Psychology, 28,* 1–14.

Doehring, D. G., & Rosenstein, J. (1960). Visual word recognition by deaf and hearing children. *Journal of Speech and Hearing Research, 3,* 320–326.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in nonsearch task. *Perception and Psychophysics, 16,* 143–149.

Finney, E. M., & Dobkins, K. R. (2001). Visual contrast sensitivity in deaf versus hearing populations: Exploring the perceptual consequences of auditory deprivation and experience with a visual language. *Cognitive Brain Research, 11,* 171–183.

Grafman, J. (2001). Conceptualizing functional neuroplasticity. *Journal of Communication Disorder, 33,* 345–355.

Henderson, S. E., & Henderson, L. (1973). Levels of visual-information processing in deaf and hearing children. *American Journal of Psychology, 86,* 507–521.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology, Human Perception and Performance, 21,* 451–468.

Lavie, N., & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. *Psychological Science, 8,* 395–398.

Loke, W. H., & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society, 29,* 437–440.

Marendaz, C., Robert, C., & Bonthoux, F. (1997). *Deafness and attentional visual search: A developmental study.* Paper presented at the European Conference on Visual Perception.

Marschark, M. (1993). Learning to read and write. In *Psychological development of deaf children* (pp. 203–225). Oxford: Oxford University Press.

Maylor, E., & Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychology of Aging, 13,* 563–573.

Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients and perceptual load: A search for boundary conditions. *Perception and Psychophysics, 49,* 270–288.

Mills, C. (1985). Perception of visual temporal patterns by deaf and hearing adults. *Bulletin of the Psychonomic Society, 23,* 483–486.

Myklebust, H. R. (1950). *Keystone non-language charts.* Meadville, PA: Keystone View Co.

Myklebust, H. R., & Brutten, M. A. (1953). A study of the visual perception of deaf children. *Acta Oto-laryngologica, Supplement, 105.*

Netelenbos, J. B., & Savelsbergh, G. J. P. (1991). Localization of visual targets inside and outside the field of view: The effect of hearing loss. *Journal of Child Psychology and Psychiatry, 32,* 983–993.

Neville, H. J. (1990). Intermodal competition and compensation in development. In A. Diamond (Ed.), *The development and neural bases of higher cognitive function* (pp. 71–91). New York: New York Academy of Sciences Press.

Neville, H. J., Bavelier, D., Corina, D. P., Rauschecker, J. P., Karni, A., Lalwani, A., Braun, A., Clark, V. P., Jezzard, P., & Turner, R. (1998). Cerebral organization for language in deaf and hearing subjects: Biological constraints and effects of experience. *Proceedings of the National Academy of Sciences, U.S.A., 95,* 922–929.

Neville, H. J., & Lawson, D. S. (1987a). Attention to central and peripheral visual space in a movement detection task: An event-related potential and behavioral study: I. Normal hearing adults. *Brain Research, 405,* 253–267.

Neville, H. J., & Lawson, D. S. (1987b). Attention to central and peripheral visual space in a movement detection task: An event related potential and behavioral study: II. Congenitally deaf adults. *Brain Research, 405,* 268–283.

Neville, H. J., & Lawson, D. S. (1987c). Attention to central and peripheral visual space in a movement decision task: III. Separate effects of auditory deprivation and acquisition of a visual language. *Brain Research, 405,* 284–294.

Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition, 4,* 313–327.

Phippard, D. (1977). Hemifield differences in visual perception in deaf and hearing subjects. *Neuropsychologia, 15,* 555–561.

Poizner, H., & Tallal, P. (1987). Temporal processing in deaf signers. *Brain and Language, 30,* 52–62.

Quittner, A. L., Smith, L. B., Osberger, M. J., Mitchell, T. V., & Katz, D. B. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5,* 347–353.

Radell, P. L., & Gottlieb, G. (1992). Developmental intersensory interference: Augmented prenatal sensory experience interferes with auditory learning in duck embryos. *Developmental Psychology, 28,* 795–803.

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science, 278,* 1616–1619.

Rettenbach, R., Diller, G., & Sireteanu, R. (1999). Do deaf people see better? Texture segmentation and visual search compensate in adult but not in juvenile subjects. *Journal of Cognitive Neuroscience, 11,* 560–583.

Reynolds, H. N. (1993). Effects of foveal stimulation on peripheral visual processing and laterality in deaf and hearing subjects. *American Journal of Psychology, 106,* 523–540.

Roder, B., Teder-Salejarvi, W., Sterr, A., Rosler, F., Hillyard, S., & Neville, H. (1999). Improved auditory spatial tuning in blind humans. *Nature, 400,* 162–166.

Ross, P. (1983). Cerebral specialization in deaf individuals. In Segalowitz (Ed.), *Language functions and brain organization* (pp. 287–313). New York: Academic Press.

Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research, 37,* 495–510.

Sireteanu, R., & Rettenbach, R. (2000). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research, 40,* 2925–2949.

Stivalet, P., Moreno, Y., Richard, J., Barraud, P.-A., & Raphel, C. (1998). Differences in visual search tasks between congenitally deaf and normally hearing adults. *Cognitive Brain Research, 6,* 227–232.

Teder-Salejarvi, W., Hillyard, S., Roder, B., & Neville, H. (1999). Spatial attention to central and peripheral auditory stimuli as indexed by event-related potentials. *Brain Research, Cognitive Brain Research, 8,* 213–227.

Turkewitz, G., & Kenny, P. A. (1982). Limitations on input as a basis for neural organization and development. *Developmental Psychobiology, 15,* 357–368.

Werner, H., & Strauss, A. A. (1942). Experimental analysis of the clinical symptom 'perseveration' in mentally retarded children. *American Journal of Mental Deficiency, 47,* 185–188.