Brain and Cognition **49,** 152–169 (2002)
doi:10.1006/brcg.2001.1497

The Effects of Spatial Attention on Motion Processing in Deaf Signers, Hearing Signers, and Hearing Nonsigners

Rain G. Bosworth and Karen R. Dobkins

University of California, San Diego

Visual abilities in deaf individuals may be altered as a result of auditory deprivation and/or because the deaf rely heavily on a sign language (American Sign Language, or ASL). In this study, we asked whether *attentional* abilities of deaf subjects are altered. Using a direction of motion discrimination task in the periphery, we investigated three aspects of spatial attention: orienting of attention, divided attention, and selective attention. To separate influences of auditory deprivation and sign language experience, we compared three subject groups: deaf and hearing native signers of ASL and hearing nonsigners. To investigate the ability to *orient* attention, we compared motion thresholds obtained with and without a valid spatial precue, with the notion that subjects orient to the stimulus *prior* to its appearance when a precue is presented. Results suggest a slight advantage for deaf subjects in the ability to orient spatial attention. To investigate *divided attention,* we compared motion thresholds obtained when a single motion target was presented to thresholds obtained when the motion target was presented among confusable distractors. The effect of adding distractors was found to be identical across subject groups, suggesting that attentional capacity is not altered in deaf subjects. Finally, to investigate selective attention, we compared performance for a single, cued motion target with that of a cued motion target presented among distractors. Here, deaf, but not hearing, subjects performed better when the motion target was presented among distractors than when it was presented alone, suggesting that deaf subjects are more affected by the presence of distractors. In sum, our results suggest that attentional orienting and selective attention are altered in the deaf and that these effects are most likely due to auditory deprivation as opposed to sign language experience.

Key Words: deaf; sign language; motion perception; visual attention.

INTRODUCTION

The ability of the brain to reorganize itself in response to the removal of a sensory modality, a phenomenon referred to as ‘‘cross-modal plasticity,’’ has been well documented in the animal literature (see Rauschecker, 1995, for a review). In humans, the study of congenitally blind or deaf subjects affords the opportunity to investigate the perceptual consequences of modality-specific sensory deprivation. Consistent with the animal literature, the results from such studies generally suggest that the absence of one sensory modality leads to enhanced representation of intact modalities. For example, compared to sighted subjects, blind people have been shown to possess superior tactile discrimination (Axelrod, 1959; Sadato, Pascual-Leone, Graf-

This work was supported by NSF Grant SBR9870897 (K.R.D.). We are grateful to the deaf and hearing individuals who volunteered for this study, to Joanne Bundalian and Tracy Deboer for assistance in running subjects and data analysis, and to Amy Rezec and Eva Finney for comments on the article.

Address correspondence and reprint requests to Karen R. Dobkins, Department of Psychology, 0109, University of California, San Diego, La Jolla, CA 92093. E-mail: kdobkins@ucsd.edu.

0278-2626/02 $35.00

man, Ibanez, Deiber, Dold, & Hallet, 1996; Van Boven, Hamilton, Kauffman, Keenan, & Pascual-Leone, 2000) and auditory localization (Lessard, Pare, Lepore, & Lassonde, 1997; Muchnik, Efrati, Nemeth, Malin, & Hildesheimer, 1991; Roder, Rosler, & Hennighausen, 1997) abilities. A possible neural basis for these perceptual findings has been provided in brain imaging studies (Kujala, Huotilainen, Sinkkonen, Ahonen, Alho, Hamalainen et al., 1995; Sadato et al., 1996) which have demonstrated responses to tactile or auditory stimuli in the visual cortex of blind subjects.

In deaf subjects, perceptual and neural imaging studies have similarly been conducted in order to investigate the potential for cross-modal plasticity (e.g., Levänen, Jousmäki, & Hari, 1998; Neville, Schmidt, & Kutas, 1983), although here the results have been far more equivocal. With regard to the visual perceptual abilities of deaf subjects, most studies have focused on higher level ‘‘visual-cognitive’’ performance. In this domain, deaf subjects have been shown to exhibit enhanced capabilities along the dimensions of face processing (Bettger, Emmorey, McCullough, & Bellugi, 1997; McCullough & Emmorey, 1997), mental rotation (Emmorey, Kosslyn, & Bellugi, 1993), and gestalt completion (Siple, Hatfield, & Caccamise, 1978). In general, enhancement of these abilities is thought to be the result of experience with sign language, since comprehension and production of American Sign Language (ASL) depends heavily on such cognitive and visuospatial abilities (see Emmorey, 1995, for a review). One way to ascertain whether enhancement of visual abilities in deaf subjects is due to their experience with sign language, as opposed to their deafness *per se,* is to compare three groups of subjects: deaf native signers, hearing native signers, and hearing nonsigners. Both hearing and deaf native signers have experienced early exposure to ASL from their deaf signing parents, while hearing signers and nonsigners both have normal hearing. Thus, those aspects of performance that are common to both hearing and deaf signers suggest an influence of sign language experience. By contrast, those aspects of performance observed in deaf signers, yet not in hearing signers or nonsigners, can be attributed to auditory deprivation. Supporting the notion that signing experience is responsible for enhanced visual-cognitive abilities in the deaf, the studies mentioned above have shown that hearing signers also exhibit superior abilities.

In contrast to results obtained for higher level tasks, studies investigating *low-level* visual perception have generally failed to observe clear differences between deaf signers and hearing nonsigners. For example, abilities such as contrast sensitivity (Finney & Dobkins, 2001), brightness judgment (Bross, 1979), temporal resolution (Bross & Sauerwein, 1980; Mills, 1985; Poizner & Tallal, 1987), and identification of unfamiliar characters (Hartung, 1970) do not appear to differ between groups. Although such results suggest that neither deafness or sign language experience alters low-level sensory processing, others have proposed that deaf and hearing subjects may differ in their ability to *attend* to low-level visual stimuli, specifically for stimuli in the periphery. For example, previous studies have reported that deaf subjects are faster and more accurate than hearing subjects at detecting (Loke & Song, 1991) and discriminating (Neville & Lawson, 1987) stimuli presented in the periphery, but not in the center, of gaze. The authors of these studies interpreted these results as evidence that deaf subjects possess enhanced peripheral attention, which they attributed to increased vigilance in the periphery. Although enhanced peripheral attention in the deaf is a viable interpretation, it is important to point out that these studies cannot rule out the possibility that superior performance in the periphery instead reflects enhanced *sensory* processing in the periphery of deaf subjects.

Only a handful of perceptual studies have employed classic attention paradigms to investigate differences in attentional abilities between deaf and hearing subjects. Reviewed here are three aspects of attention—attentional orienting, divided attention, and selective attention. Investigating attentional orienting, Parasnis and Samar (1985) used a spatial precueing paradigm to measure reaction times for the detection of validly cued vs invalidly cued targets. For both deaf and hearing subjects, they found longer reaction times for invalidly cued stimuli, presumably because in this condition subjects must reorient their attention from the invalid location to the target location, which takes time. However, deaf subjects were found to be less impaired by invalid cues than hearing subjects, leading the authors to conclude that deaf subjects are faster at reorienting attention from one location to another. As we address below under *Discussion* (and see Pashler, 1998), it is possible that their results may instead reflect differences in decision criteria between deaf and hearing subjects rather than differences in orienting abilities.

In addition to studies investigating attentional orienting across the visual field, others have looked at *divided attention*, i.e., the ability to process multiple stimuli in the visual field. One typical approach has been to employ a visual search paradigm wherein subjects must detect the presence or absence of a ‘‘target’’ stimulus presented among confusable ‘‘distractors’’ (for examples, see Bergen & Julesz, 1983; Treisman & Gelade, 1980; Wolfe, 1994). The results of such studies demonstrate that, under certain stimulus conditions, reaction time increases as the number of items in the display increases, a phenomenon referred to as ‘‘set-size effect’’ (e.g., Estes & Taylor, 1966). Early theories of visual attention interpreted this result as evidence that visual processing proceeded in a *serial* fashion, presumably because attentional resources are limited in capacity (e.g., Broadbent, 1958). Using this visual search paradigm, Stivalet, Moreno, Richard, Barraud, and Raphel (1998) and Rettenbach, Diller, and Sireteanu (1999) reported greater set-size effects in hearing, as compared to deaf, subjects and interpreted this as evidence for greater attentional capacity in deaf individuals. As we address under *Discussion* (and see Palmer, 1994), however, these set-size effects may instead reflect differences in the ability to discriminate targets from distractors rather than differences in attentional capacity.

A final area of investigation in hearing and deaf subjects has involved experiments that measure *selective attention*, i.e., the ability to selectively attend to one item while ignoring other distracting stimuli. For example, deaf subjects have been shown to possess a superior ability to selectively attend to peripheral stimuli while ignoring centrally presented distractors (Parasnis & Samar, 1985; Reynolds, 1993; and see Proksch & Bavelier, 2002, for a similar interpretation of enhanced peripheral attention using a perceptual load task). That visual attention in the deaf may be enhanced for the periphery is supported by both visually evoked potential studies (Neville & Lawson, 1987) and functional magnetic resonance imaging studies (Bavelier, Tomann, Hutton, Mitchell, Corina, Liu, & Neville, 2000), which have demonstrated greater attentionally related neural responses in deaf as compared to hearing subjects for peripheral, but not central, stimuli. In sum, evidence across diverse studies suggests that deaf subjects may possess an enhanced ability to selectively attend to peripheral stimuli.

In the present study, we investigated these three main aspects of spatial attention in deaf and hearing subjects, (1) orienting of attention, (2) divided attention, and (3) selective attention, using a direction-of-motion discrimination paradigm we have previously employed to study these issues in hearing subjects (Dobkins & Bosworth, 2001). We chose to investigate motion processing for several reasons. First, previous evidence in animals suggests that this aspect of visual perception may be especially susceptible to changes following altered sensory input (Chalupa, Meissirel, & Lia, 1996; Neville, 1995). Second, devoid of auditory cues to orient them to peripheral stimuli, deaf subjects may rely particularly heavily on the motion of objects in their peripheral vision (e.g., in the case of crossing a busy street). Finally, motion of the hands is an integral part of the acquisition and comprehension of ASL, and thus, there is reason to believe that the increased reliance on such motion cues may enhance or alter motion perception. To assess whether potential differences between deaf and hearing groups result from experience with sign language or auditory deprivation, we tested a third group, hearing native signers who learned ASL early in life from their deaf parents.

In order to investigate the ability to orient attention, we compared motion discrimination thresholds and reaction times obtained when a precue alerted subjects to the location of a to-be-presented motion stimulus to those obtained when no precue was provided. In the precue condition, subjects can orient attention to the stimulus location prior to its appearance. By contrast, without a precue, orienting occurs once the stimulus appears. In this latter case, the time spent orienting to the stimulus presumably occurs at the expense of processing time, and thus, performance is expected to be impaired without a precue (see Dobkins & Bosworth, 2001). Using this paradigm, we predicted that the faster a subject can orient to the onset of the stimulus, the smaller the benefit of the precue would be on thresholds. Thus, if deaf signers are relatively fast at orienting attention to the uncued stimulus, they should exhibit smaller benefits of precueing than the other groups.

In order to investigate the ability to divide attention across multiple visual stimuli, we compared motion thresholds obtained when a single motion target was presented (referred to as ‘‘set-size 1’’) to those obtained when that target was presented among three confusable noise distractors (referred to as ‘‘set-size 4’’). To identify the mechanism underlying the observed set-size effects, relative performance in the two conditions was compared to predictions from quantitative models of unlimited vs limited capacity. This paradigm allowed us to address whether attentional capacity differs between deaf and hearing subjects, as suggested by Rettenbach et al. (1999) and Stivalet et al. (1998).

Finally, in order to investigate selective spatial attention, we compared thresholds obtained for a single, cued motion target with those obtained for a cued motion target presented among distractors. By comparing the effect of distractors upon performance, we addressed whether the ability to selectively attend to a target while ignoring distractors differs between deaf and hearing subjects.

In sum, these experiments investigated whether overall motion sensitivity or spatial attention differs across our three subject groups. Results that differ between deaf signers and both hearing groups can be attributed to auditory deprivation, while differences observed between native signers (both deaf and hearing) and hearing nonsigners suggest effects of sign language experience. Note that the data obtained in this experiment were also used to investigate visual field asymmetries in the three subject groups, and those results are presented in our companion article (see Bosworth & Dobkins, 2002b).

METHODS

Subjects

Forty-one subjects participated in this experiment. Sixteen were deaf signers of American Sign Language, all of whom had an 80-decibel or greater loss in both ears. Of this group, 12 were born deaf, 2 acquired deafness due to illness, and 2 reported an unknown etiology. The deaf subjects used ASL as their primary language and were exposed to ASL between birth and 5 years of age, either because they had one or two deaf signing parents or because they attended a school where sign language was used. Ten subjects were hearing signers, who were exposed to ASL since birth because they had deaf, signing parents. Fifteen subjects had normal hearing, spoke only English, and had no exposure to ASL beyond fingerspelling.

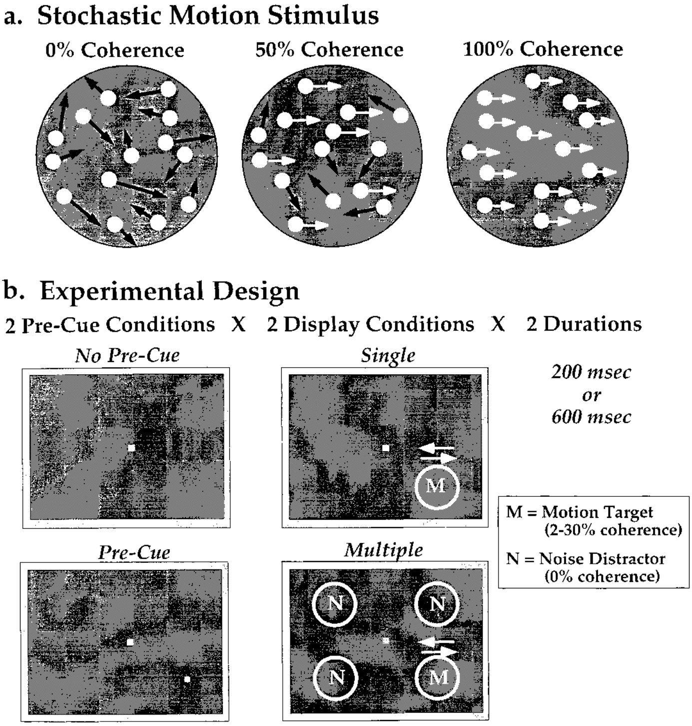

FIG. 1. (a) Examples are shown for three different percentages of coherent motion (0, 50, and 100%). White arrows represent the coherent motion of signal dots. Black arrows represent the random motion of noise dots. Coherence levels were varied across trials to obtain thresholds. (b) The design consisted of two precueing conditions (no precue vs precue), two display conditions (single vs multiple), and two stimulus durations (200 ms vs 600 ms).

All subjects had normal or corrected-to-normal vision, were right-handed, reported no neurological abnormalities, and were naive to the purpose of the experiment. Deaf and hearing native signers were recruited from the San Diego deaf community. Hearing nonsigners were recruited from the student population at University of California, San Diego. The mean ages of the three subject groups were as follows: deaf signers: 31.1 ± 9.1 years; hearing signers: 31.5 ± 12.5 years; and hearing nonsigners: 28.1 ± 9.3 years. There was no significant difference in age across groups [$F(2, 38) = 0.68$, $p = 0.51$].

Apparatus

Visual stimuli were generated using a SGT Pepper Graphics board (Number Nine Computer Corporation: 640 × 480 pixel resolution, 60-Hz frame rate) residing in a Pentium-based PC and were displayed on a Nanao video monitor with a 21-inch display.

Eye position was monitored using a closed couple device (CCD) infrared camera with variable focus (12.5 to 75 mm) lens (Model No. Fc62, Image Sensor), which was focused on the left eye of the subject. Each subject's face was lit with an infrared illuminator, and an enlarged image of the eye was viewed on a 12-inch monitor (Ultrak) outside the testing room. Before beginning each block of trials, subjects were instructed to fixate on a small green square (0.35°) in the center of the video display. Using this set-up, saccadic eye movements could easily be detected, and eye drift as little as 2° of fixation could be discerned. Eye movements were rare, occurring on less than two trials for any subject.

Stimuli

Motion thresholds were obtained using a *stochastic motion stimulus* (after Newsome & Paré, 1988; Williams & Sekuler, 1984). This stimulus consists of a field of white dots presented within a circular aperture, wherein a proportion of ‘‘signal’’ dots moves in a coherent direction (‘‘leftward’’ or ‘‘rightward’’) while the remaining ‘‘noise’’ dots move in a random fashion (see Fig. 1a). The signal proportion is varied across trials in order to obtain a *coherent motion threshold,* the percentage of moving signal dots required to yield 75% correct directional discrimination. In our display, the motion stimulus consisted of 119 dots (each 0.12° in diameter) presented within an 8.0° diameter aperture (dot density = 2.4 dots/degree^2). The moving signal dots were displaced 0.35° from one frame to the next, with each frame lasting 50 ms, resulting in a dot speed of 6.9°/s. The trajectory for each moving dot lasted two frames (i.e., 100 ms). The dot then reappeared in a random location within the circular aperture and moved coherently for another two frames, and so on. Each noise dot was repositioned in a random location from frame to frame. The luminance of all dots was 26 cd/m^2, presented against a black background (0.3 cd/m^2).

In order to obtain coherent motion thresholds, seven different levels of coherence were tested in equal log steps (base 1.58) from 2 to 30%. These stimuli were presented in random fashion across trials (method of constant stimuli), in one of the four quadrants of visual space—lower left, lower right, upper left, and upper right. In order to study the effects of additional ''noise distractors'' on motion performance, stochastic motion stimuli containing 0% coherence were employed in some conditions (see below).

General Procedures

Subjects were tested in a darkened room and viewed the video display binocularly from a chin rest situated 57 cm away. Subjects were instructed to maintain fixation on a small green square in the center of the monitor for the duration of each trial. Subjects initiated each trial with a key press, 50 ms after which the stochastic motion stimulus appeared randomly in one of the four quadrants of visual space, centered 15.4° eccentric to fixation (vertical eccentricity = ±9.0°, horizontal eccentricity = ± 12.5°). These eccentricity values were chosen as they approximate a typical distance of the signer's hands from an observer's fixation (Bosworth, Wright, Bartlett, Corina, & Dobkins, 2000). Subjects reported perceived direction of motion (''leftward'' vs ''rightward'') by pressing one of two appropriate keys. Negative feedback was provided for incorrect trials, which consisted of a white circle (2.3° diameter, 26 cd/m^2) presented 2.3° below the fixation square for 200 ms. Although subjects were not instructed to respond in a speeded fashion, as the emphasis in this study was accuracy, reaction times were obtained for all conditions. For all subjects, instructions were provided by the first author (R.G.B.), who is fluent in both ASL and spoken English.

Experimental Design

Data were obtained for 8 conditions, in a 2 (display type) × 2 (spatial precueing) × 2 (stimulus duration) factorial design (see *Fig. 1b).* The two *display conditions* were (1) ''single display,'' the target motion stimulus was presented alone in one of the four quadrants of visual space; and (2) ''multiple display,'' the target motion stimulus was presented in one visual field quadrant while the three remaining quadrants contained noise distractors (i.e., stochastic motion stimuli with 0% motion coherence). The two *precueing conditions* were (1) ''no precue,'' subjects were uncertain as to which visual quadrant the target would appear in. In the single display condition, the location of the motion target was unknown prior to its appearance; however, because of the high luminance contrast of the stimulus, its location was obvious once it was presented. In the multiple display condition, the noise distractors were confusable with the motion target, and thus there was uncertainty regarding the location of the target. (2) ''Precue,'' subjects were alerted to the location of the to-be-presented motion target with a 0.23° square (26 cd/m^2) that appeared beforehand in the center of that location (i.e., centered 15.4° eccentric to fixation in one of the four visual field locations). The significance of the precue was explained to subjects, and they were instructed to use the cue to their benefit. Thus, on trials that contained a precue, subjects knew to focus attention on the appropriate location of visual space before beginning a trial. When the precue was presented in the multiple display condition, subjects were informed that the three uncued locations of visual space would contain noise that should be ignored. Subjects initiated the trial with a key press, and 50 ms later the precue disappeared and the stimulus (or stimuli) was presented. We chose to employ this cueing method to ensure that subjects adequately processed the precue before the stimulus was presented (i.e., that they were ''ready'' for the stimulus). We measured the amount of time subjects took to initiate each trial and found that the cue duration time was, on average, approximately 550 ms ($SD = 300$ ms). No significant differences were found between the three groups in cue duration time [$F(2, 36) = 1.18$; $p = 0.35$].

The two different stimulus durations in our experiment were 200 and 600 ms. Each of the eight different stimulus conditions was tested in separate blocks. In order to minimize order and practice effects, half of the total trials were obtained for each condition before repeating this again. The order of the blocks was randomized and counterbalanced across subjects (with the exception that no subject was first tested on a block of the multiple, no precue, 200-ms condition, since this was the most difficult).

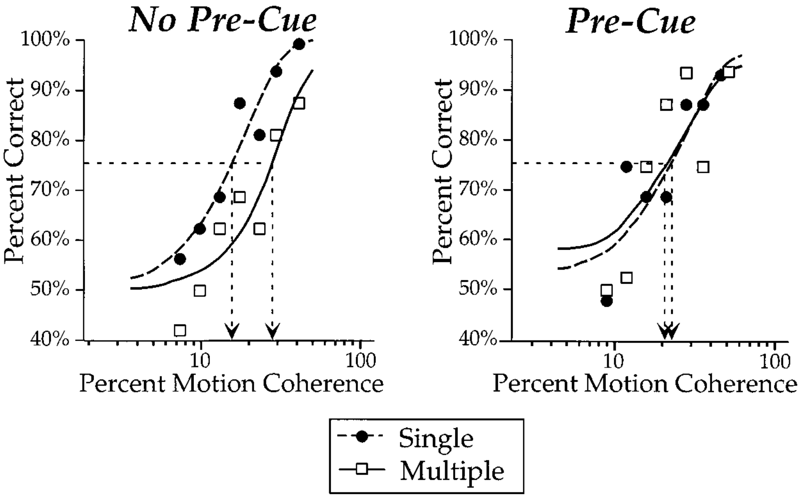

FIG. 2. Data from one deaf subject are plotted for no precue *(left panel)* and precue *(right panel)* conditions. Percentage correct is plotted as a function of percentage coherent motion in order to obtain thresholds. Separate functions are plotted for single *(dashed line, solid circles)* and multiple *(solid line, open squares)* display conditions. Each function was obtained from 112 trials. In this particular example, the stimulus was presented in the upper left visual field and the stimulus duration was 200 ms.

The experiment consisted of 3584 total trials (448 trials per condition) after practice on 400 trials. Subjects typically required approximately 4 hours over 2 sessions within 1 week to complete the experiment.

Data Analysis

Coherent motion thresholds. Psychometric curves were fit to the data using Weibull functions and maximum likelihood analysis (Weibull, 1951; Watson, 1979), with threshold defined as the coherence level yielding 75% correct performance. Thresholds were obtained for each condition and for each of the four visual field locations in which the motion target appeared. Thresholds were averaged across the four locations for each subject.

Threshold ratios. In order to investigate precueing effects, thresholds for the no precue condition were divided by thresholds for the precue condition (i.e., $\mathrm{Thr}_{\text{No Precue}}:\mathrm{Thr}_{\text{Precue}}$) for each duration and display type. To investigate set-size effects, thresholds for the multiple, uncued (''set-size 4'') condition were divided by those for the single, uncued (''set-size 1'') condition (i.e., $\mathrm{Thr}_{\text{Set-size 4}}:\mathrm{Thr}_{\text{Set-size 1}}$). To investigate the effect of distractors on performance, thresholds for the multiple, cued condition were divided by those for the single, cued condition (i.e., $\mathrm{Thr}_{\text{Multiple, cued}}:\mathrm{Thr}_{\text{Single, cued}}$). These ratios were calculated for each subject and then averaged within each subject group.

Reaction time differences. Although this was not a speeded reaction time study, we nonetheless analyzed reaction time data.[1] For each subject, a mean reaction time was obtained by averaging the data obtained for the different motion coherence levels and the four visual field locations.[2] In order to compare performance between conditions, reaction time differences (i.e., $\mathrm{RT}_{\text{No Precue}} - \mathrm{RT}_{\text{Precue}}$, $\mathrm{RT}_{\text{Set-size 4}} - \mathrm{RT}_{\text{Set-size 1}}$, and $\mathrm{RT}_{\text{Multiple, cued}} - \mathrm{RT}_{\text{Single, cued}}$) were computed for each subject before averaging across subjects.

RESULTS

Example Data

Example psychometric functions from one subject are shown in Fig. 2. Percentage correct performance is plotted as a function of percentage motion coherence. Data

---

[1] Reaction time data were obtained for 39 of the 41 subjects. For two subjects, these data were not obtained because the portion of our program that recorded this had not yet been completed.

[2] For each subject, trials with reaction time values 3 or more standard deviations above the subject's mean were considered outliers. These outliers were substituted with a value 2 standard deviations above the subject's mean for that condition. This occurred in less than 2.2% of all cases.

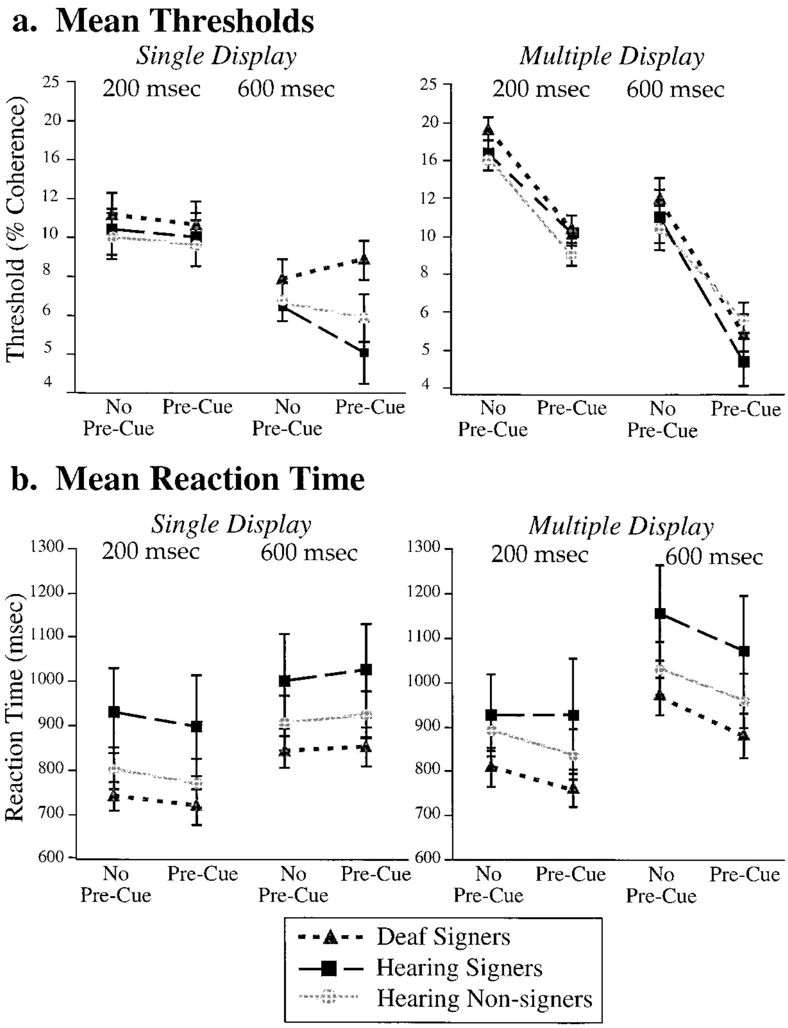

FIG. 3. *Group mean thresholds (a) and reaction times (b)* for deaf signers (triangles, $n = 16$), hearing signers (squares, $n = 10$), and hearing nonsigners (circles, $n = 15$). (Left) Single display data and (right) multiple display data are shown. For each graph, data are plotted separately for each duration, 200 and 600 ms. Error bars denote standard errors of the means.

in this example were obtained from the 200-ms condition and are plotted separately for the no precue (*left panel*) and precue (*right panel*) conditions. For each plot, data are shown for single (*dashed lines, solid circles)* and multiple (*solid lines, open squares)* display conditions. From these functions, thresholds were calculated as the percentage coherence value for which the subject performed at 75% correct. Note that in the no precue condition, the threshold for the multiple condition was higher than that for the single condition. For the precue condition, the two display types yielded similar thresholds.

Mean Thresholds and Reaction Times: Comparison across Subject Groups

Group mean data from each of the three subject groups (deaf signers, hearing signers and hearing nonsigners) are plotted in Fig. 3 separately for each condition. The subject groups performed comparably in terms of thresholds [$F(2, 38) < 1.0$]

and reaction times [$F(2, 36) = 1.78$, $p > 0.05$]. Specifically, averaged across all conditions, mean thresholds were 9.9, 8.5, and 8.7% and mean reaction times were 818, 990, and 888 ms, respectively, for deaf signers, hearing signers, and hearing nonsigners. Post hoc comparisons also revealed no differences in thresholds between *hearing* subjects (hearing signers and nonsigners combined) and *deaf* subjects [$F(1, 38) = 1.81$; $p > 0.05$], nor between *signers* (deaf and hearing signers' data combined) and *nonsigners* [$F(1, 38) < 1.0$]. Thus, we found no evidence that auditory deprivation or sign language experience leads to overall enhanced motion sensitivity. There is, however, a slight trend for deaf subjects to be faster yet less accurate than the other groups, suggesting small differences across groups in speed–accuracy tradeoffs.

Orienting of Attention

In order to investigate how well subjects can orient attention to a peripherally presented stimulus, we measured the benefit of the precue by dividing subjects' thresholds obtained in the single, no precue condition by those obtained when a precue alerted the subject to the location of the to-be-presented motion stimulus ($\mathrm{Thr}_{\mathrm{No\ Precue}}:\mathrm{Thr}_{\mathrm{Precue}}$). Here, ratios greater than 1.0 indicate that the presence of the precue improved motion performance, while ratios lower than 1.0 indicate that the precue impaired performance.

In the past, we (Dobkins & Bosworth, 2001) have hypothesized that one potential function of the precue in the single display condition may be to eliminate the time spent orienting attention to the stimulus and thereby increase the time processing the stimulus. That is, in the precue condition, the subject's attention is expected to be directed to the stimulus location *prior* to its onset, whereas in the no precue condition, the subject must orient attention to the stimulus during the stimulus presentation. By this account, thresholds should be lower in the precue condition because processing time is effectively increased. More importantly, the faster a subject can orient attention to a peripherally presented stimulus, the smaller the benefit of the precue should be (i.e., the smaller the $\mathrm{Thr}_{\mathrm{No\ Precue}}:\mathrm{Thr}_{\mathrm{Precue}}$ ratio). From this, we predicted that if deaf subjects are faster at orienting attention (as suggested by Parasnis & Samar, 1985), they should exhibit a smaller cueing benefit than hearing subjects in the single display condition.

To address this prediction, group mean data for the single display condition are shown in Fig. 4. Because the effect of precueing was not significantly different between the two stimulus durations [threshold ratios: $F(1, 38) < 1.0$; reaction time differences: $F(1, 36) < 1.0$], data for the 200- and 600-ms conditions have been combined here. The results of this analysis revealed no significant differences in threshold ratios between the three subject groups [$F(2, 38) = 2.24$; $p > 0.05$]. However, there was a trend for deaf subjects to exhibit lower threshold ratios relative to hearing subjects. Specifically, the mean threshold ratio was 0.98 for deaf subjects and 1.13 for hearing signers and nonsigners combined, and this effect was marginally significant [$t(39) = 1.68$; $p = 0.05$]. Although only suggestive, this smaller effect of precueing on deaf subjects' thresholds suggests faster orienting to peripheral stimuli in deaf subjects as a consequence of auditory deprivation. This effect, however, was not observed in reaction time differences, as there was no significant effect of subject group [$F(2, 36) < 1.0$]. Not surprisingly, this lack of a group main effect on reaction time differences may be a result of the fact that our task did not require subjects to respond in a speeded manner.

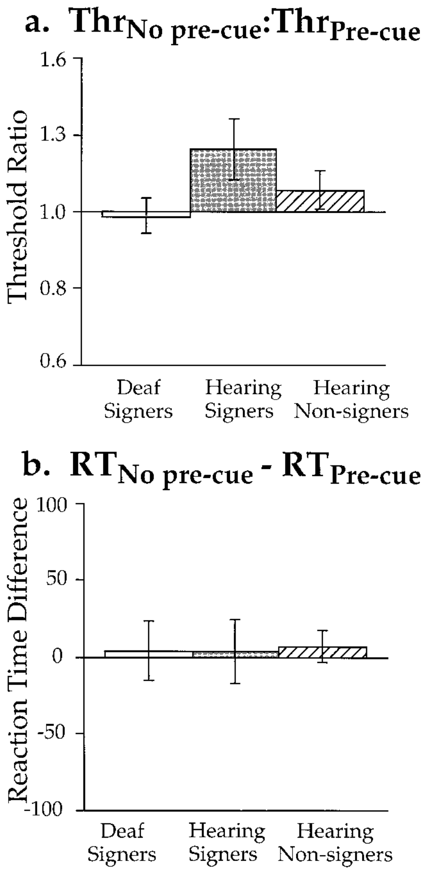

FIG. 4. (a) Group mean threshold ratios ($\text{Thr}_{\text{No Precue}}:\text{Thr}_{\text{Precue}}$) for the single display condition. Data have been collapsed across the two stimulus durations (200 and 600 ms), as there was no effect of duration on threshold ratios. Ratios greater than 1.0 indicate better performance in the precue, than in the no precue, condition. Deaf subjects exhibited lower threshold ratios (i.e., less cueing benefit) than hearing signers and nonsigners combined, suggesting that attentional orienting may be slightly better in the deaf. (b) Corresponding group mean reaction time differences ($\text{RT}_{\text{No Precue}} - \text{RT}_{\text{Precue}}$). Here, no differences existed across subject groups. Error bars denote standard errors of the means.

Divided Attention

In order to investigate the ability to divide attention across multiple stimuli, we compared performance for the no precue, multiple display condition with performance for the no precue, single display condition. As mentioned in the *Introduction,* our single display condition is equivalent to a set-size of 1, while our multiple display condition is equivalent to a set-size of 4 (i.e., one target motion stimulus presented simultaneously with three distractor noise stimuli). For each subject, a threshold ratio was obtained by dividing the threshold for set-size 4 by the threshold for set-size 1 (i.e., $\text{Thr}_{\text{Set-size 4}}:\text{Thr}_{\text{Set-size 1}}$).

Group mean threshold ratios are plotted in Fig. 5a. Because set-size effects for the two durations were not significantly different from one another [$F(1, 38) < 1.0$], data for the 200- and 600-ms conditions have been combined here. All subject groups displayed ratios greater than 1.0, indicating better performance for set-size 1 than for set-size 4. There was no significant difference between the three groups for threshold ratios [$F(2, 38) < 1.0$]. Averaged across duration and subject groups, the mean

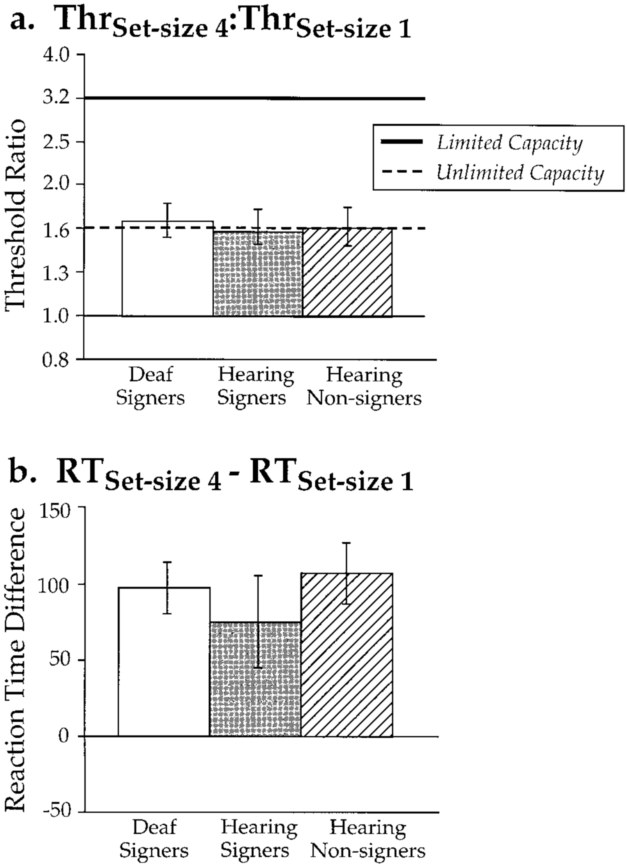

FIG. 5. (a) Group mean threshold ratios ($\mathrm{Thr}_{\text{Set-size 4}}:\mathrm{Thr}_{\text{Set-size 1}}$). Data have been collapsed across the two stimulus durations (200 and 600 ms), as there was no effect of duration on threshold ratios. Ratios greater than 1.0 indicate worse performance for set-size 4 than for set-size 1. Predicted threshold ratios are shown for unlimited capacity (*dashed line*) and limited capacity (*solid line*) models (see text). All three subject groups yielded ratios that were extremely close to those predicted by the unlimited capacity model. (b) Corresponding group mean reaction time differences ($\mathrm{RT}_{\text{Set-size 4}} - \mathrm{RT}_{\text{Set-size 1}}$). All subject groups were slower for set-size 4, indicating that poorer thresholds for this condition were not due to speed–accuracy trade-offs. Error bars denote standard errors of the means.

threshold ratio was 1.58, which was significantly greater than 1.0 [$t(40) = 8.40$, $p < 0.0001$]. For comparison, we have plotted mean reaction time differences (i.e., $\mathrm{RT}_{\text{Set-size 4}} - \mathrm{RT}_{\text{Set-size 1}}$) in Fig. 5b. Here, mean reaction time was significantly faster (by 95 ms) for set-size 1 than set-size 4 [$t(38) = 7.66$, $p < 0.001$], and there were no differences across groups [$F(2, 36) < 1.0$]. Because reaction time data mirror threshold data, our findings cannot be explained by a speed–accuracy trade-off.

These set-size effects indicate that performance on this motion task suffers when subjects are uncertain regarding the location of the target and must divide their attention across multiple visual stimuli. Two models have been put forth to explain why impairment in performance occurs with increasing set-size. *Limited capacity models* postulate that set-size effects occur because increasing the number of visual stimuli to be attended necessarily degrades the quality of processing for each.[3] By contrast,

---

[3] Limited attentional capacity is also commonly used to explain the finding that *reaction times* in search paradigms increase with increasing set-size (e.g., Broadbent, 1958; Treisman & Gelade, 1980). Here, set-size effects are thought to arise because limited capacity requires subjects to search, in a serial fashion, each item in the display. The relevance of this theory in the context of previous related studies of visual attention in the deaf is addressed further under *Discussion.*

unlimited capacity models posit that the quality of sensory processing does *not* change as the number of items to be attended increases, but rather that visual performance is worse for larger, as compared to smaller, set-sizes due to an increased probability for errors occurring at the *decision level.*

These two models yield quantitatively distinct predictions for the effects of set-size on visual thresholds. The theories and equations behind these models, which are based on Signal Detection Theory, are described in detail previously (see Dobkins & Bosworth, 2001). In brief, these models assume that performance on the motion task is mediated by an ‘‘ideal observer’’ who monitors the outputs of neurons (referred to as ‘‘detectors’’) tuned to different directions of motion (e.g., leftward vs rightward). The ideal observer makes a decision (‘‘leftward’’ or ‘‘rightward’’) based on the directional detector (leftward or rightward detector) with the maximal activation (referred to as the ‘‘maximum rule’’). When there is *unlimited capacity,* the activity in these detectors is unaffected by increasing set-size, yet performance is expected to decline because the presence of noise distractors increases the overall probability of decision errors. Specifically, this unlimited capacity model predicts that thresholds should be 1.60 times higher for set-size 4 than for set-size 1 ($\text{Thr}_{\text{Set-size 4}}/\text{Thr}_{\text{Set-size 1}} = 1.60$). The *limited capacity* model also assumes that a maximum rule decision is employed. However, owing to attentional resources needing to be divided among the number of visual stimuli presented, the variance of activity in each detector rises proportionally with increasing set-size. Here, the predicted threshold ratio is 3.20.

Predicted threshold ratios for the two models of attention are presented along with the group mean ratios in *Fig. 5a:* limited capacity *(solid line)* and unlimited capacity *(dashed line).* Observed threshold ratios were significantly different from the predictions for limited capacity [$t(40) = 12.10$; $p < 0.0001$], indicating that this model does not provide an adequate fit to the data. By contrast, each group’s mean ratio was not significantly different from the predicted ratio for the unlimited capacity model ($p > 0.70$ for each comparison), indicating that this model can adequately account for the observed set-size effects for all three groups. In sum, for all subject groups, these set-size results support the unlimited capacity model of attention, demonstrating that the visual motion system can divide attention among several stimuli simultaneously with no cost to sensory processing *per se.* Moreover, these results suggest comparable attentional capacity for deaf and hearing subjects and are thus contradictory to previous claims that deaf subjects possess greater attentional capacity (Rettenbach et al., 1999; Stivalet et al., 1998). We address this discrepancy between studies further in the *Discussion.*

Selective Attention

In order to investigate whether the effect of distractors on motion discrimination performance differs across deaf signers, hearing signers, and hearing nonsigners, we divided thresholds in the multiple, cued condition by those in the single, cued condition ($\text{Thr}_{\text{Multiple, cued}} : \text{Thr}_{\text{Single, cued}}$). If the effect of the precue in the multiple display condition is to eliminate entirely the influence of the three noise distractors, resulting threshold ratios should be 1.0. That is, the multiple, cued display condition should be equivalent to presenting a single motion target in the visual field. By comparison, threshold ratios greater than 1.0 indicate that the distractors impaired performance, whereas values below 1.0 indicate performance was facilitated in the presence of the distractors.

Group mean threshold ratios are shown in Fig. 6a and corresponding reaction time differences are presented in Fig. 6b. Interestingly, for 600-ms stimuli, the mean

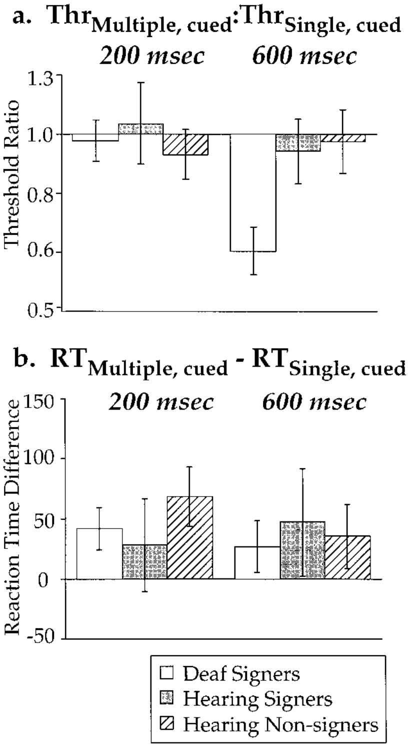

FIG. 6. (a) Group mean threshold ratios (Thr$_{\text{Multiple, cued}}$:Thr$_{\text{Single, cued}}$) for 200- *(left)* and 600-ms *(right)* duration stimuli. Ratios greater than 1.0 indicate better performance in the absence of distractors. For the 600-ms stimulus, deaf subjects exhibited ratios *less* than 1.0, indicating superior performance when the target was presented among ignored noise distractors compared to when the target was presented alone. (b) Corresponding group mean reaction time differences (RT$_{\text{Multiple, cued}}$ − RT$_{\text{Single, cued}}$). Error bars denote standard errors of the means.

threshold ratio for deaf subjects was significantly less than 1.0 [$t(15) = -4.94$; $p < 0.0002$], indicating that noise distractors in the multiple, cued display condition *improved* performance. Specifically, the mean threshold ratio for deaf subjects at this duration was 0.59 (representing a 1.7-fold improvement in performance), and this value was significantly different from that observed in hearing subjects [$F(1, 38) = 8.94$, $p = 0.005$]. Note, however, that this effect was not mirrored in reaction time differences, where all three subject groups' reaction times were 30 to 60 ms slower in the multiple, cued condition, and there were no differences across groups [$F(1, 36) < 1.0$]. Thus, at least for threshold data, only at the longer duration, the results of these analyses suggest that deaf subjects are more affected by the presence of distractors.

DISCUSSION

The main goal of these experiments was to investigate whether attentional processes differ between deaf and hearing subjects. Employing a direction-of-motion discrimination paradigm, we investigated three different aspects of visual spatial attention: orienting of attention, divided attention, and selective attention. In our attentional orienting manipulation, we hypothesized that the degree of precueing benefit in the single display condition provides an estimate of how well attention can be oriented to the stimulus location at its onset. Here, we found that deaf signers benefited from the precue less than the two hearing groups did (although this effect was only marginally significant), suggesting that deaf subjects are better than hearing subjects at orienting attention to a peripheral stimulus.[4] Because this effect was observed in deaf, and not hearing, signers, this effect appears to be related to auditory deprivation rather than experience with sign language.

In a previous study, Parasnis and Samar (1985) similarly concluded that deaf subjects were better at orienting attention. In their study, they measured speeded reaction times for detecting validly vs invalidly cued luminance increments presented to the left or right of fixation. Typically when this paradigm is employed, reaction times are found to be longer for invalidly cued trials, which is interpreted as reflecting the time required for subjects to reorient attention from the invalidly cued location to the target location. Because these authors found that, compared to hearing subjects, deaf subjects were less slowed by invalid precues, they concluded that deaf subjects are faster at reorienting attention. However, it is important to point out that their task and paradigm may not, in fact, have measured the time to orient attention. Rather, because they used a simple reaction time task (i.e., subjects respond as soon as they detect the stimulus) instead of a choice reaction time task (i.e., subjects perform a visual discrimination on the stimulus), longer reaction times for the invalidly cued trials in this paradigm may reflect a stricter decision criterion, with no need to entertain a theory of attentional orienting (see Pashler, 1998, for discussion). Thus, their results might instead reflect differences between deaf and hearing subjects in decision criteria rather than orienting abilities. In addition, since the potential target locations in the Parasnis and Samar study were quite close to one another (only 2° to the left and right of fixation), it is questionable whether their task required orienting of attention at all. Nonetheless, the results of Parasnis and Samar, as well as those of the present study, are consistent with the notion that deaf subjects may possess a superior ability to orient attention.

To investigate divided attention, we quantified set-size effects (by comparing thresholds in the multiple, uncued condition with the single, uncued condition) in order to determine whether attentional resources for this task are limited in capacity. Here, we found that set-size effects in all three subject groups could be well accounted for by an unlimited capacity model. Thus, at least with respect to direction of motion discrimination, the results of our study do not support differences in attentional capacity between deaf and hearing subjects. At first glance, this result may appear to contradict the results of Rettenbach et al. (1999) and Stivalet et al. (1998). These investigators employed a visual search paradigm to measure set-size effects in deaf and hearing subjects. In these studies, set-size effects were obtained by measuring reaction times for detecting a target among distractors as a function of the number of distractors. Because deaf subjects exhibited smaller set-size effects than hearing subjects, the authors concluded that attentional capacity is greater in deaf subjects. However, this conclusion is based on an assumption that large set-size effects reflect limited capacity. Specifically, reaction time is thought to increase with increasing set-size because capacity limitations prevent subjects from processing multiple stimuli simultaneously, requiring instead that subjects search the display items in a ‘‘serial’’ fashion.

While this is one possible explanation, another viable alternative has been proposed

---

[4] Note that, although we have presented our precueing results as a way to measure the ability to orient attention to a stimulus at its onset, we should point out that precueing benefits may instead reflect an enhancement of the stimulus representation (e.g., Carrasco & Yeshurun, 1998; Lu & Dosher, 1998; and see Dobkins & Bosworth, 2001). In this scenario, smaller precueing benefits observed in deaf subjects, as compared to hearing subjects, would reflect a lesser degree of perceptual enhancement in the deaf. However, we think this explanation is unlikely since many studies fail to report perceptual enhancement for single display conditions (Pashler, 1998).

(see Shaw, 1980 and Palmer, 1994). As discussed under *Results*, set-size effects can also be explained even when attention is *unlimited* in capacity, since performance is expected to decline with increasing set-size simply because the target is confusable with the distractors, and thus, the addition of distractors produces more chances for a distractor to be mistaken for a target at the decision level (i.e., a ‘‘false alarm’’). In the case of a speeded reaction time study, reaction times are expected to increase with increasing set-size to compensate for the greater likelihood for decision errors. By this account, the large set-size effects observed in hearing subjects in the reaction time studies by Rettenbach et al. (1999) and Stivalet et al. (1998) may not reflect limited attentional capacity but rather the fact that the target is confusable with the distractors. If discriminability can, in fact, explain their set-size effects, the finding of smaller set-size effects in deaf subjects, relative to hearing subjects, may reflect a superior ability for deaf subjects to discriminate targets from distractors, rather than increased attentional capacity.

It is also important to point out that the finding of unlimited capacity in the present study does not rule out the possibility that deaf subjects may exhibit greater attentional capacity in other tasks that are more likely to reveal limited capacity. An example of such a task is the dual-task paradigm (e.g., Braun & Julesz, 1998; Lee, Koch, & Braun, 1997; Prinzmetal, Amiri, Allen, & Edwards, 1998). Here, subjects’ performance on a main task is measured under conditions of full attention vs degraded attention, the latter being produced by requiring subjects to perform a concurrent, attentionally demanding task *while* the main task is being performed. Typically, performance on the main task suffers under conditions of degraded attention, which is explained by supposing that attentional resources for the main task are depleted by the concurrent task. This paradigm may be particularly fruitful for studies of visual attention in the deaf population, and such studies will soon be underway in our laboratory.

Last, our experiments allowed us to investigate how well subjects can selectively attend to a target stimulus in one region of visual space while ignoring distractors in other regions (by comparing thresholds in the multiple, cued condition to those in the single, cued condition). Here, we found that, for 600-ms stimuli, deaf subjects performed 1.7-fold better in the multiple, cued condition than in the single, cued condition. This surprising result suggests that the addition of uncued, ignored noise patches in the periphery actually *facilitated* performance in the deaf. Similarly, using a form discrimination task, Proksch and Bavelier (2002) also reported an increased effect of peripheral distractors upon target processing in deaf subjects, despite the fact that subjects were instructed to ignore the distractors. Two possible interpretations may explain our effect. First, the task of ignoring distractors in order to attend to the target in the multiple, cued condition may require increased effort, which, in turn, may improve processing of the target. Thus, our results could potentially be explained by proposing that, relative to hearing subjects, deaf subjects expend more ‘‘top-down’’ cognitive effort when trying to ignore irrelevant stimuli. The fact that the enhanced performance in the presence of distractors was observed only for the 600-ms duration might reflect the fact that such top-down processes require more time to take effect. A second ‘‘bottom-up’’ explanation concerns the possibility that the sensory processing of a motion stimulus is enhanced by the presence of surrounding noise stimuli and, importantly, that this occurs at a preattentive level, where stimuli can affect basic processing even when those stimuli are volitionally ignored. Support for this possibility comes from neurophysiological responses obtained from directionally selective neurons in macaque medial temporal (MT) area (e.g., Allman, Miezin, & McGuinness, 1985; Born & Tootell, 1992). These previous studies showed that the response of an individual MT neuron to preferred motion in its receptive field is often augmented when additional moving stimuli are placed in the area of visual space surrounding the classic receptive field. Although the surrounding patches in our study contained only noise, rather than motion signals, it is possible that noise stimuli might produce a similar effect, which is particularly strong in the deaf.

On a final note, in addition to investigating differences in attentional abilities, the results of our study allowed us to address differences in *absolute* performance across subject groups. Although it might be predicted that deaf individuals' lifelong experience with a visual language (in which motion cues are crucial) and their increased reliance upon visual cues in general would enhance their motion sensitivity, the results of the present study, as well as those of our previous study (Bosworth & Dobkins, 1999), indicate no differences between deaf signers and hearing nonsigners in this domain. These null results join other failures to observe low-level perceptual differences between deaf and hearing subjects for capacities such as contrast sensitivity (Finney & Dobkins, 2001), discrimination of temporal patterns (Mills, 1985), and brightness judgment (Bross, 1979). However, note that in the present study, subjects discriminated gross differences in direction (i.e., ‘‘leftward’’ vs ‘‘rightward’’). Thus, the possibility remains that other forms of motion processing, such as the ability to discriminate very small differences in direction of motion, may be altered in deaf subjects. For example, the fine discriminations in the movements of fingerspelling are extremely important for comprehension of sign language (Wilcox, 1992), and thus testing these finer directional discriminations may reveal enhanced motion perception in the deaf.

REFERENCES

Allman, J., Miezin, F., & McGuinness, E. (1985). Direction- and velocity-specific responses from beyond the classical receptive field in the middle temporal visual area (MT). *Perception,* **14**(2), 105–126.

Axelrod, S. (1959). Effects of early blindness: Performance of blind and sighted children on tactile and auditory tasks. *American Foundation for the Blind, Research Series,* **7,** 83.

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience,* **20**(93), 1–6.

Bergen, J. R., & Julesz, B. (1983). Rapid discrimination of visual patterns. *IEEE Transactions on Systems, Man, & Cybernetics,* **13**(5), 857–863.

Bettger, J., Emmorey, K., McCullough, S., & Bellugi, U. (1997). Enhanced facial discrimination: Effects of experience with American Sign Language. *Journal of Deaf Studies and Deaf Education,* **2,** 223–233.

Born, R. T., & Tootell, R. B. (1992). Segregation of global and local motion processing in primate middle temporal visual area. *Nature,* **357**(6378), 497–499.

Bosworth, R. G., & Dobkins, K. R. (1999). Left-hemisphere dominance for motion processing in deaf signers. *Psychological Science,* **10**(3), 256–262.

Bosworth, R. G., & Dobkins, K. R. (2002b). Visual field asymmetries for motion processing in deaf and hearing signers. *Brain and Cognition,* **49,** 170–181.

Bosworth, R. G., Wright, C. E., Bartlett, M. S., Corina, D., & Dobkins, K. R. (2000). *Characterization of the visual properties of American Sign Language.* Presented at the Theoretical Issues in Sign Language Research, 7th biannual conference, Amsterdam, The Netherlands.

Braun, J., & Julesz, B. (1998). Withdrawing attention at little or no cost: Detection and discrimination tasks. *Perception & Psychophysics,* **60**(1), 1–23.

Broadbent, D. E. (1958). *Perception and communication.* London: Pergamon Press.

Bross, M. (1979). Residual sensory capacities of the deaf: A signal detection analysis of a visual discrimination task. *Perceptual & Motor Skills,* **48**(1), 187–194.

Bross, M., & Sauerwein, H. (1980). Signal detection analysis of visual flicker in deaf and hearing individuals. *Perceptual & Motor Skills,* **51**(3), 839–843.

Carrasco, M., & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual search. *Journal of Experimental Psychology: Human Perception & Performance,* **24**(2), 673–692.

Chalupa, L. M., Meissirel, C., & Lia, B. (1996). Specificity of retinal ganglion cell projections in the embryonic rhesus monkey. *Perspectives on Developmental Neurobiology,* **3,** 223–231.

Dobkins, K. R., & Bosworth, R. G. (2001). Effects of set-size and selective spatial attention on motion processing. *Vision Research,* **41,** 1501–1517.

Emmorey, K. (1995). Processing the dynamic visual-spatial morphology of signed languages. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 29–54). Hillsdale, NJ: Erlbaum.

Emmorey, K., Kosslyn, S. M., & Bellugi, U. (1993). Visual imagery and visual-spatial language: Enhanced imagery abilities in deaf and hearing ASL signers. *Cognition,* **46**(2), 139–181.

Estes, W. K., & Taylor, H. A. (1966). Visual detection in relation to display size and redundancy of critical elements. *Perception & Psychophysics,* **1**(1), 9–16.

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**(1), 171–183.

Hartung, J. (1970). Visual perceptual skill, reading ability, and the young deaf child. *Psychological Monographs,* **52,** 6–22.

Kujala, T., Huotilainen, M., Sinkkonen, J., Ahonen, A., Alho, K., Hamalainen, M., Ilmoniemi, R., Kajola, M., Knuutila, J., & Lavikainen, J. (1995). Visual cortex activation in blind humans during sound discrimination. *Neuroscience Letters,* **183,** 143–146.

Lee, D. K., Koch, C., & Braun, J. (1997). Spatial vision thresholds in the near absence of attention. *Vision Research,* **37**(17), 2409–2418.

Lessard, J. M., Pare, M., Lepore, F., & Lassonde, M. (1997). Sound localization in early blind human subjects. *Society for Neuroscience Abstracts,* **23,** 2067.

Levänen, S., Jousmäki, V., & Hari, R. (1998). Vibration-induced auditory cortex activation in a congenitally deaf adult. *Current Biology,* **8,** 869–872.

Loke, W. H., & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society,* **29**(5), 437–440.

Lu, Z.-L., & Dosher, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research,* **38**(9), 1183–1198.

McCullough, S., & Emmorey, K. (1997). Face processing by deaf ASL signers: Evidence for expertise in distinguishing local features. *Journal of Deaf Studies and Deaf Education,* **2**(4), 212–222.

Mills, C. B. (1985). Perception of visual temporal patterns by deaf and hearing adults. *Bulletin of the Psychonomic Society,* **23**(6), 483–486.

Muchnik, C., Efrati, M., Nemeth, E., Malin, M., & Hildesheimer, M. (1991). Central auditory skills in blind and sighted subjects. *Scandinavian Audiology,* **20**(1), 19–23.

Neville, H. J. (1995). Developmental specificity in neurocognitive development in humans. In S. G. Michael (Ed.), *The cognitive neurosciences* (pp. 219–231). Cambridge, MA: MIT Press.

Neville, H. J., & Lawson, D. (1987). 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**(2), 268–283.

Neville, H. J., Schmidt, A., & Kutas, M. (1983). Altered vision-evoked potentials in congenitally deaf adults. *Brain Research,* **266**(1), 127–132.

Newsome, W. T., & Paré, E. B. (1988). A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *Journal of Neuroscience,* **8**(6), 2201–11.

Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks. *Vision Research,* **34**(13), 1703–1721.

Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition,* **4**(3), 313–327.

Pashler, H. E. (1998). *The psychology of attention.* Cambridge, MA: MIT Press.

Poizner, H., & Tallal, P. (1987). Temporal processing in deaf signers. *Brain and Language,* **30**(1), 52–62.

Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of attention. I. Color, location, orientation, and spatial frequency. *Journal of Experimental Psychology: Human Perception & Performance,* **24**(1), 261–282.

Proksch, J., & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience,* in press.

Rauschecker, J. P. (1995). Compensatory plasticity and sensory substitution in the cerebral cortex. *Trends in Neurosciences,* **18**(1), 36–43.

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**(5), 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**(4), 523–540.

Roder, B., Rosler, F., & Hennighausen, E. (1997). Different cortical activation patterns in blind and sighted humans during encoding and transformation of haptic images. *Psychophysiology,* **34**(3), 292–307.

Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M. P., Dold, G., & Hallett, M. (1996). Activation of the primary visual cortex by Braille reading in blind subjects. *Nature,* **380**(6574), 526–528.

Shaw, M. L. (1980). Identifying attentional and decision-making components in information processing. In R. S. Nickerson (Ed.), *Attention and Performance VIII* (pp. 277–296). Hillsdale, NJ: Erlbaum.

Siple, P., Hatfield, N., & Caccamise, F. (1978). The role of visual perceptual abilities in the acquisition and comprehension of sign language. *American Annals of the Deaf,* **123**(7), 852–856.

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**(3), 227–232.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology,* **12**(1), 97–136.

Van Boven, R. W., Hamilton, R. H., Kauffman, T., Keenan, J. P., & Pascual-Leone, A. (2000). Tactile spatial resolution in blind braille readers. *Neurology,* **54**(12), 2230–2236.

Watson, A. B. (1979). Probability summation over time. *Vision Research,* **19**(5), 515–522.

Weibull, W. (1951). A statistical distribution function of wide applicability. *Journal of Applied Mechanics,* **18,** 292–297.

Wilcox, S. (1992). *The Phonetics of Fingerspelling.* Amsterdam: Benjamins.

Williams, D. W., & Sekuler, R. (1984). Coherent global motion percepts from stochastic local motions. *Vision Research,* **24**(1), 55–62.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review,* **1**(2), 202–238.