

Event-Related Potential Studies of Cerebral Specialization during Reading

II. Studies of Congenitally Deaf Adults

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We investigated inter- and intrahemispheric specialization in congenitally deaf adults during a word reading task. The results were compared with those obtained from a group of normally hearing subjects in a paradigm which we have shown produces reliable behavioral and event-related potential (ERP) evidence of cerebral specialization (Neville, Kutas, and Schmidt (*Brain and Language*, 16, 300-315 (1982)). The deaf subjects (Ss) were as accurate as the hearing Ss in identifying the words; however, they did not display visual field asymmetries. Deaf Ss' ERPs recorded over posterior brain regions were similar in morphology to ERPs from hearing Ss but were different in lateral distribution. At the temporal and frontal regions ERPs from deaf Ss differed from those of hearing Ss in both morphology and lateral distribution. In particular, the negative (410 msec)-positive shift prominent in the left hemisphere of hearing Ss was not evident in deaf Ss. Testable hypotheses concerning the factors which may have determined the different pattern of cerebral organization in the deaf Ss are discussed.

While the description and analysis of the different specializations of the cerebral hemispheres in the adult have received much attention, little is known about the ontogeny of this aspect of brain organization. In 1967, Lenneberg proposed that the functional specializations of the two hemispheres in the adult are preceded in ontogeny by a period of relative hemispheric equipotentiality. As evidence, he cited studies reporting that lesions to both the left and right hemispheres have disruptive (though transient) effects on language. He further noted reports of virtually nor-

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mal development of language and nonlanguage skills after early left or right hemispherectomy. Results of dichotic listening studies in normal children at that time also seemed to agree with the notion that hemispheric specialization develops over the course of 10 or 12 years (Bryden & Allard, 1973; Satz, 1973; Bakker, Satz, Goebel, & van der Vlugt, 1973).

However, more recent clinical reports of the differential effects of early unilateral brain lesions (Woods & Teuber, 1978) and early hemispherectomy (Dennis & Whitaker, 1976, 1977) seem to argue against the notion of early hemispheric equipotentiality. Moreover, behavioral (Schulman-Galambos, 1977; Entus, 1977), anatomical (Wada, Clarke, & Hamm, 1975), and electrophysiological (Molfese, 1977) asymmetries similar to those found in adults have also been reported in young infants. These results have been interpreted as evidence that the functional specializations of the two cerebral hemispheres are predetermined at or before birth, and are not dependent on specific experiences (Kinsbourne, 1975; Kinsbourne & Hiscock, 1977).

These results, as well as those from earlier studies documenting the regular onset and sequence of language milestones across different cultures (Lenneberg, 1967), suggest that the maturational course of language-relevant neural processes is strongly biologically determined. However, it is likely that in humans, as in other animals, species-specific biological factors underlying neurobehavioral development interact with early experience to specify cerebral organization in the adult. In support of this notion are reports of marked alterations in the electrophysiological responses to sensory stimulation in adults whose early sensory experience has been abnormal (Freeman & Thibos, 1973; Neville, Schmidt, & Kutas, submitted). However, very little research has been directed toward describing the effects of experience on the development of the neural substrates underlying language acquisition.

One approach to this question has been to study cerebral organization in adults who have had different language experiences such as with phonetic versus ideographic language or with the acquisition of two as opposed to one language. These literatures have been characterized by contradictory reports (see Walters & Zatorre, 1978). Nonetheless, in a recent monograph on bilingualism, Albert and Obler (1978) concluded that the brains of bilinguals may be different from those of monolinguals, suggesting that language experience may play a role in determining brain organization.

An important group of people to study from this point of view are those congenitally deaf individuals who have acquired neither speech nor language through the auditory modality, but who rather have learned a visual-manual (sign) language. Studies of these persons provide information on how characteristics of the primary language can affect the

neural systems associated with language and nonlanguage processes. Such studies also provide a new perspective for evaluating current formulations of left-hemisphere functions such as (a) the motor control of speech (Levy, 1969), (b) the processing of complex acoustic information which contains rapid frequency transitions (Schwartz & Tallal, 1980), (c) the perception of temporal sequences (Efron, 1963a, 1963b) and (d) linguistic processes involved in the grammatical recoding of information (Liberman, 1974).

Currently, rather little is known about functional cerebral specializations in the deaf. The electrophysiological and behavioral evidence for left-hemisphere specialization in deaf Ss during the performance of non-language tasks in which hearing Ss showed right-hemisphere advantages suggests that the acquisition of sign language does indeed alter the course of cerebral organization (Neville, 1977; Neville & Bellugi, 1978). If the left hemisphere is specialized for the production and perception of sign language, then it may also be predominant in certain nonlanguage functions that are integral to the use of the sign language. However, the diversity of methods employed and results obtained from clinical and visual half-field investigations of cerebral specialization for sign language make it difficult to answer this question (for discussion see Neville & Bellugi, 1978; Poizner, Battison, & Lane, 1979).

Hearing children first acquire the vocabulary and grammar of English through the auditory modality, and then bring this knowledge to the task of learning to read. In contrast, congenitally deaf children often learn to read English through picture-grapheme association in the visual modality. This different experience of the deaf might alter the course of cerebral specialization for reading (i.e., where the left hemisphere normally plays a greater role than the right). Evidence on this question is sparse and equivocal. Of the few visual half-field studies in which English words were presented to deaf Ss, as many reported a right visual field advantage (left hemisphere), as a left visual field advantage (right hemisphere), while others have found no asymmetry in accuracy of word identification (Manning, Goble, Markman, & LaBrecche, 1977; McKeever, Hoemann, Florian, & VanDeventer, 1976; Kelly & Tomlinson-Keasey, 1977; Poizner et al., 1979). However, hemispheric processes associated with the perception of English *per se* may have been confounded in these studies as they required Ss to respond either after translating the word into sign or by matching the word to a picture. Ss may be more likely to continue processing the words as English if they were required to produce the word in written English.

Clearly, it would be advantageous to monitor neurophysiological processes in the two hemispheres while deaf Ss process language information. In fact, techniques have been developed which permit continuous monitoring of the electrical potentials of the brain associated with stim-

ulus and cognitive events ("event-related cerebral potentials" or ERPs; for reviews see Goff, Allison, & Vaughan, 1978; Starr, Sohmer, & Cellesia, 1978; Hillyard, Picton, & Regan, 1978). While many ERP studies of hemispheric specialization in hearing Ss have had methodological shortcomings, or have failed to find evidence for cerebral specialization (for reviews see Donchin, Kutas, & McCarthy, 1977; Hillyard & Woods, 1979), recent studies employing natural language stimuli or designs producing behavioral lateral asymmetries have reported seemingly reliable evidence for cerebral specialization (Shucard, Shucard, & Thomas, 1977; Neville, 1974, 1980; Kutas & Hillyard, 1980).

In a companion paper (Neville, Kutas, & Schmidt, 1982), we reported large and reliable differences in the amplitude and morphology of ERPs recorded over different areas of the two hemispheres while hearing adults performed a reading task. The lateral ERP asymmetries were observed in parallel with behavioral evidence for left-hemisphere specialization on the task. To the extent that ERPs from this paradigm reflect aspects of normal cerebral functioning, they could be sensitive to changes in brain organization after different early language experiences. With this in mind, we investigated the behavior and ERPs of congenitally deaf adults when they read English words which required a written response and compared them with the results obtained from normally hearing Ss.

METHODS

Subjects

Eight right-handed deaf adults (5 female, 3 male, mean age = 25 years, Edinburgh laterality quotient = 0.87) with normal or corrected vision were paid to participate in the experiment. All Ss were free of other neurological disorders. Each S was profoundly deaf and had been so since birth, and had at least one congenitally deaf relative.¹ The major form of communication employed by these Ss was American Sign Language (ASL). Results from these Ss are compared with those from ten right-handed hearing adults, reported in Neville et al. (1982).

Stimuli, Procedure, ERP Recording, and Data Analysis

All methods were identical to those reported in the companion study of hearing Ss. Briefly, the stimuli were four-letter English nouns presented for 100 msec randomly 1.6° to the left or right visual field, or two different words were presented bilaterally. Subjects fixated on the center of the display where a colon or semicolon appeared simultaneously with the word(s). Subjects pressed a button to indicate which fixation symbol was presented (if they were incorrect the trial was excluded from further analyses) and then wrote the word(s) they saw. Task instructions were written in English; however, all direct communications between Ss and experimenters were in ASL.

Scalp electrical activity was recorded from left and right occipital, parietal, temporal, anterior temporal, and frontal regions and from beneath the left eye, referenced to the

¹ The most common cause of hereditary deafness is failure of the cochlea to differentiate normally in embryogenesis. Thus, the central nervous system is probably not directly affected in these Ss.

linked mastoids (system bandpass was 0.01–100 Hz). Trials with excessive eye movements or muscle artifact were rejected. ERP components were quantified by computer as either peak or area amplitudes within a specified latency range. ERPs from deaf Ss were analyzed by a four-way analysis of variance with repeated measures on the factors of hemisphere, visual field, and electrode. For deaf–hearing comparisons a five-way analysis was performed including group as a factor. We also performed a principle components analysis (PCA) on the ERPs and employed the same analysis of variance designs on the component scores.

RESULTS

I. Deaf Subjects

Behavioral Results

Ss reported words in left visual field (LVF) and right visual field (RVF) with the same overall accuracy both after unilateral (mean percentage correct LVF 66, RVF 68) and bilateral (LVF 34, RVF 36) presentations (field effect $F(1, 7) = 0.13$, NS). The mean accuracy for the fixation discrimination task was 97%.

Event-Related Potentials

Figure 1 presents ERPs at each of the electrode sites (averaged across all Ss), elicited by words presented to the RVF. It is clear that the morphology of the ERPs elicited by these stimuli varied considerably as a function of electrode position both within and between the cerebral hemispheres. Several of the ERP components showed consistent amplitude asymmetries over the two hemispheres.

Posterior ERPs (occipital and parietal regions). A comparison of the ERPs recorded over the left and right occipital regions during right, left, and bilateral visual field presentations is provided in Fig. 2. Visual inspection of these ERPs revealed that there were large differences in the waveforms over the two hemispheres.

N200. The N200 amplitude (area 150–220 msec) tended to be 2–4 μV larger from the right than the left occipital region after both LVF and bilateral word presentations and was symmetrical from the two hemispheres after RVF presentations (hemisphere \times field interaction $F(2, 14) = 3.7$, $p < .05$; see Fig. 2). At the parietal sites N200 was small and symmetrical from the two hemispheres.

N300. There was an inconsistent tendency for a negative component around 300 msec to appear more prominently in the right than the left parietal ERPs (see Fig. 1), however, measures of this region (250–400 msec) showed no statistically significant differences.

P450 and sustained positivity. The late positive shift peaking between 400 and 500 msec post stimulus (462 ± 27 msec) was quite prominent over parietal (mean = 13.7 μV) and occipital sites (mean = 11.2 μV). At each of these locations the area 500–900 tended to be symmetrically distributed for LVF and bilateral word presentations but larger over the

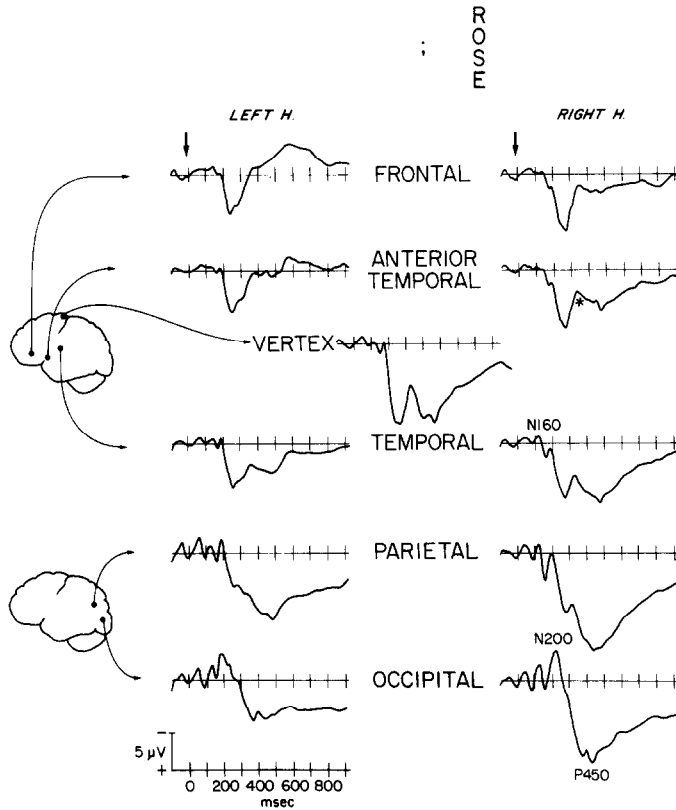


FIG. 1. Grand mean ERPs (averaged across all eight deaf Ss) from homologous locations over the left and right hemispheres and the vertex, elicited by vertically oriented words presented to the right visual field. Negativity is up on this and all subsequent figures. The dots on the schematics of the brains at the far left of the figure represent approximate locations of the various recording electrodes over the left-hemisphere scalp.

right hemisphere after RVF presentations (hemisphere \times field $F(2, 14) = 9.1, p < .002$).

Anterior ERPs (frontal, anterior temporal, and temporal): N160. The first negative component in ERPs from anterior electrodes (169 ± 8 msec) was symmetrical in amplitude from the two hemispheres (hemisphere $F(1, 7) = 1.0$, NS).

Area 300–500 msec. Following the N160 and the subsequent positivity (P250), ERPs from the two hemispheres were consistently different in morphology. The nature of this asymmetry can be seen in Figure 3, where ERPs from the left and right anterior temporal electrodes are superimposed for RVF, Bilateral and LVF word presentations. The greater negativity of ERPs from anterior regions of the left than the right hemisphere was reliable (area 300–500 msec, hemisphere $F(1, 7) = 16.9$,

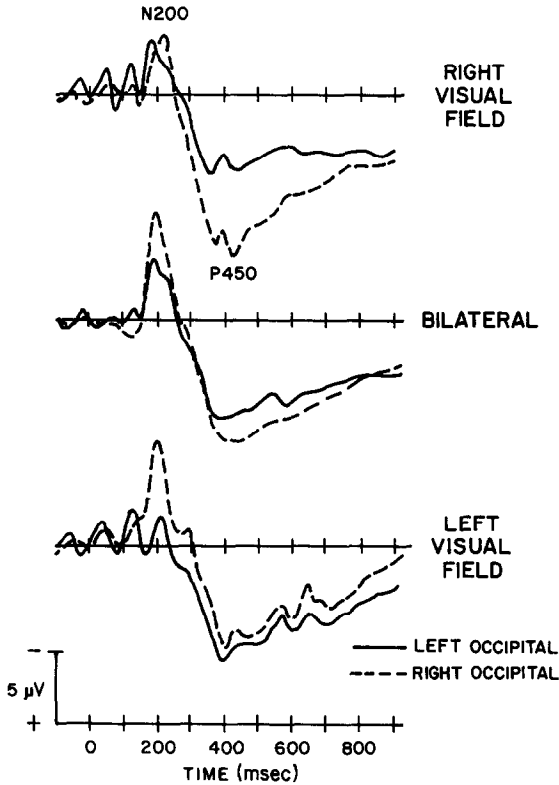


FIG. 2. A comparison of the grand mean ERPs recorded over the left (solid line) and right (dashed line) occipital regions during the right, left, and bilateral visual field word presentations.

$p < .004$) and this asymmetry was similar for all word presentations (hemisphere \times field $F(2, 14) = 1.3$, NS).

Beginning around 250 msec after word presentation, ERPs from the left anterior temporal region returned to baseline; the left frontal region became increasingly negative. In contrast, ERPs from the *right* hemisphere displayed a negative peak between 300 and 400 msec (marked by the asterisk) and then became positive before returning to baseline. As seen in Fig. 3, these differences between the hemispheres were similar whether words were presented to the RVF, LVF, or bilaterally. A peak-to-peak measure of the most negative point between 250 and 400 msec and the most positive point following it, corroborated our visual impressions that this amplitude was larger from the right than the left anterior electrodes, for all word presentations (hemisphere effect $F(1, 7) = 7.3$, $p < .003$). The consistency of this asymmetry across Ss is depicted in the scatter plot in Fig. 4.

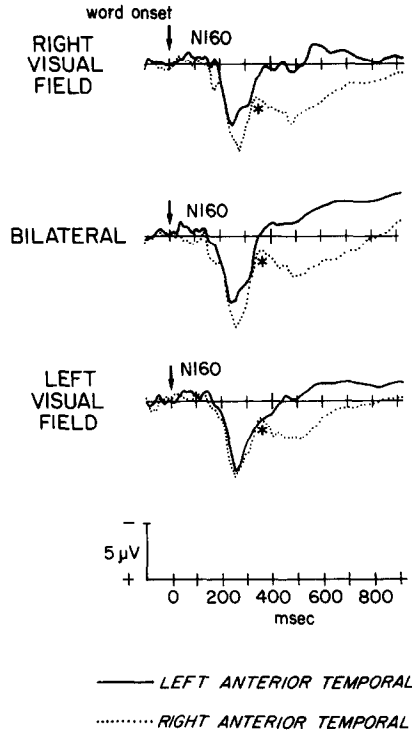


FIG. 3. A comparison of the grand mean ERPs recorded over the left (solid line) and right (dotted line) anterior temporal regions during right, left, and bilateral visual field word presentations.

Difference ERPs

Many of the ERP asymmetries are summarized in Fig. 5, which shows difference ERPs, obtained by subtracting ERPs recorded over the right hemisphere from those recorded over homologous locations on the left hemisphere. As seen in Fig. 5a, the N200 from the occipital sites tended to be larger from the right hemisphere after LVF and bilateral (but not RVF) presentations (field $F(2, 14) = 3.5$, $p < .05$); the P450 component was larger from the right hemisphere after RVF but not LVF presentations (field $F(2, 14) = 13.3$, $p < .0006$). In contrast, the asymmetries in ERPs from anterior regions Figs. 5b and c occurred in the same direction for all word presentations. The negative peak (between 300 and 400 msec) in right-hemisphere ERPs is not apparent in the difference ERPs since the two hemispheres were equally negative at that point. However, the subsequent positivity in the right-hemisphere ERPs, when subtracted from the left-hemisphere ERPs, appears as a component peaking around 600 msec in the difference wave. It is also clear from Figs. 5b and c that the magnitude of the hemisphere differences in the anterior ERPs was similar for all word presentations (field $F(2, 14) = 1.3$, NS).

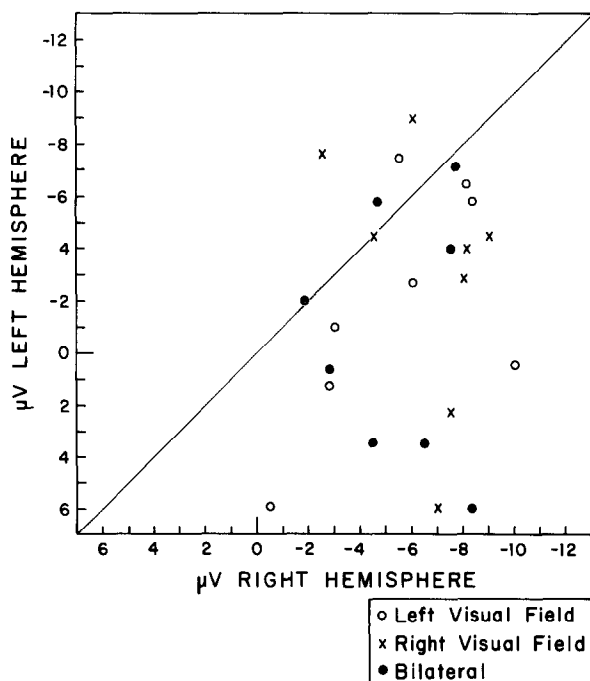


FIG. 4. A scatter plot comparing the peak to peak amplitude of the most negative point between 250 and 400 msec and most positive point after it, from the left and right anterior temporal sites for words presented to the left or right visual fields or bilaterally. A point falls below the diagonal if the right-hemisphere amplitude was larger than the left. Each mark represents the data from an individual S. The different symbols represent the values obtained from ERPs elicited by left visual field (open circles), right visual field (\times), and bilateral (closed circles) visual field word presentations.

II. COMPARISON OF RESULTS FROM DEAF AND HEARING SUBJECTS

Behavioral Results

There were no significant differences between hearing and deaf Ss in the overall accuracy of word identification either after unilateral or bilateral word presentations (group effect $F(1, 16) = 0.01$, NS). However, the two groups differed significantly when the accuracy of identification was calculated separately for right and left visual field presentations (group \times field interaction $F(1, 16) = 14.7$, $p < .001$). As shown in Fig. 6, hearing Ss showed a large advantage in reporting words after RVF presentations whereas the deaf Ss performed equally well after RVF and LVF presentations.

Event-Related Potentials

Posterior ERPs (occipital and parietal regions). The general morphologies of the ERPs elicited by the words over the posterior regions

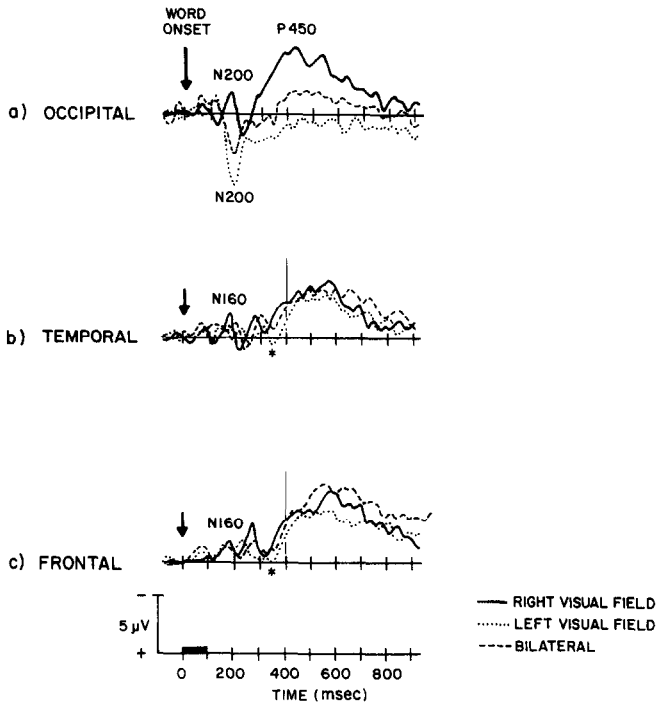


FIG. 5. Difference ERPs obtained by subtracting ERPs recorded over the right from those recorded over the left (a) occipital, (b) temporal, and (c) frontal electrodes.

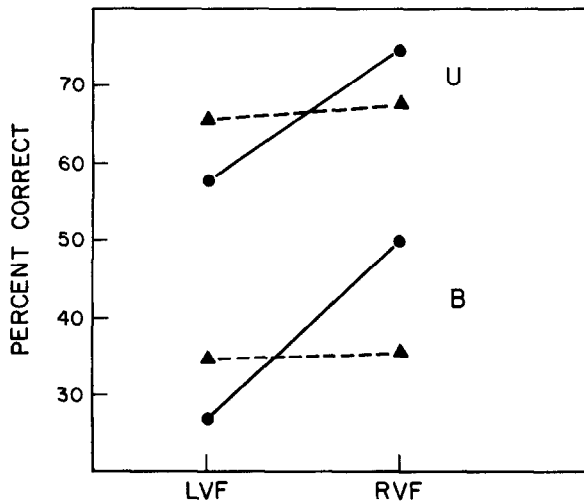


FIG. 6. Comparison of the mean percentage correct identification of vertically oriented four-letter words presented to the left (LVF) and right (RVF) visual fields in congenitally deaf and normal hearing Ss. Data are presented for unilateral (U) and bilateral (B) word presentations, separately. ●—●, hearing; ▲---▲, deaf.

were quite similar in the hearing and deaf Ss. Thus, both groups showed a large N200 and a late slow positive shift which were largest over the parietooccipital region. In both groups, the largest slow positive shifts were elicited over the right occipital and parietal regions by words presented to the right visual field.

However, while in hearing Ss the occipital N200 was larger contralateral to unilateral word presentations and was symmetrical after bilateral word presentations, in deaf Ss N200 was larger from the right hemisphere after both LVF and bilateral word presentations and was symmetric after RVF presentations.

A large difference between hearing and deaf Ss also occurred in the posterior N300 component. The hearing Ss displayed a large N300 component in the left hemisphere after RVF word presentations whereas the deaf Ss' waveforms did not show a consistent N300 under any word presentations (group \times field $F(2, 32) = 3.7, p < .03$).

Anterior ERPs (frontal, anterior temporal, and temporal). The N160 component was significantly larger from the left than the right hemisphere in hearing Ss, but was symmetrical from the two hemispheres in deaf Ss. The analysis including group as a factor was not significant.

As seen in Fig. 7, after 250 msec, ERPs over temporal and frontal

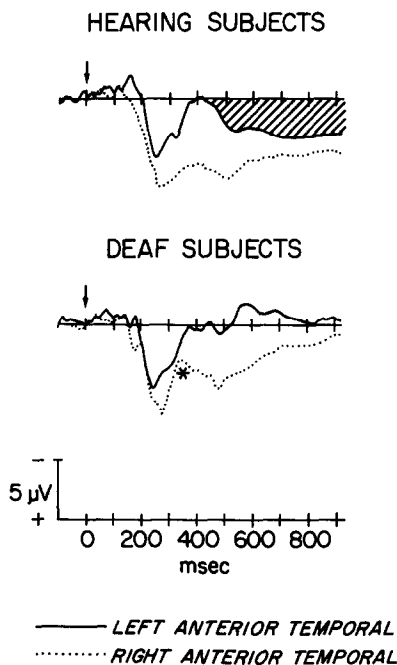


FIG. 7. A comparison of the grand mean ERPs from hearing and deaf Ss recorded over left (solid line) and right (dotted line) anterior temporal regions when words were presented to the right visual field.

regions from deaf and hearing Ss differed in general morphology and in the pattern of lateral asymmetries.

Over the left hemisphere, hearing Ss displayed a negative (N410)–positive shift (shaded area in Fig. 7) which was not evident in ERPs from the left hemisphere of deaf Ss. The area from 500–900 msec was very small or slightly negative in deaf Ss while it was positive in hearing Ss (Group $F(1, 16) = 5.5$, $p < .03$). This group difference was largest after RVF presentations (group \times field effect $F(2, 32) = 5.9$, $p < .006$).

In contrast over the right hemisphere, ERPs from hearing Ss displayed a small negativity followed by a prolonged positive shift, while deaf Ss displayed an earlier, more prominent negativity (marked by the asterisk in Fig. 7). The peak negativity between 300 and 500 msec occurred earlier in the right hemisphere of deaf than hearing Ss (group \times hemisphere $F(1, 16) = 5.7$, $p < .03$) and was more negative from the right hemisphere of deaf than hearing Ss after RVF presentations (group \times hemisphere \times field $F(2, 32) = 3.6$, $p < .03$).

Thus, while a larger negative–positive shift occurred in the left than the right hemisphere of hearing Ss, a larger shift of this type occurred in the right than the left hemisphere of deaf Ss. The amplitude from the most negative point between 300 and 500 msec to the subsequent positivity was greater from the left than right hemisphere of hearing Ss, but was greater from the right than the left hemisphere of deaf Ss (group \times hemisphere $F(1, 16) = 8.2$, $p < .01$). As seen in Fig. 8, in hearing Ss this asymmetry was most pronounced after RVF presentations while in deaf Ss it was similar for all visual field presentations.

Finally, ERPs from anterior regions of deaf and hearing Ss were also significantly different at the end of the analysis epoch; ERPs from both

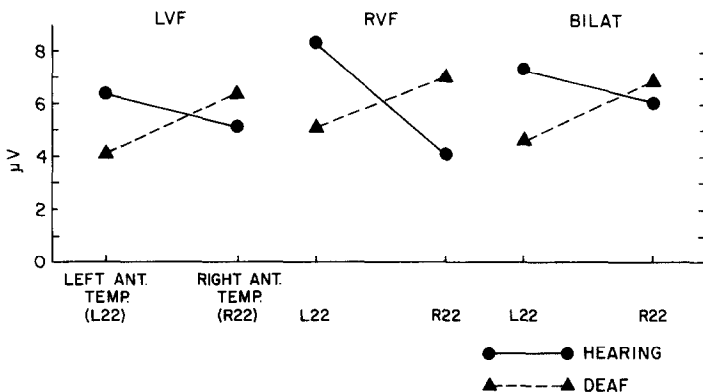


FIG. 8. A comparison of the amplitude (in microvolts) from the most negative point between 300 and 500 msec to the subsequent positivity in hearing (solid line) and deaf (dashed line) Ss from anterior temporal regions when words were presented to the left (LVF) or right (RVF) visual field or bilaterally.

hemispheres were appreciably more positive in hearing Ss than in deaf Ss (area 700–900 msec, Group $F(1, 16) = 9.1$, $p < .008$).

Principal components analysis. Visual inspection of the ERPs revealed activity in some regions that was difficult to measure using standard methods. For example, the N410 component, prominent in the left hemisphere of hearing Ss, and the negative peak in the right hemisphere of deaf Ss were both negative-going initially but were often positive with respect to the prestimulus baseline (see Fig. 7). Moreover the sustained positive shift (measured as area 500–900) may have been overlapping these negative-going components. Therefore a principle components analysis (PCA) was applied in order to describe the ERPs in terms of independent (orthogonal) sources of variance. All of the ERPs from the 8 deaf and 10 hearing Ss (i.e., 2 hemispheres, 5 positions, 3 field presentations) formed the 540 “cases”; these ERPs were sampled at 60 time points (“variables”). This 540×60 data input matrix was transformed into a covariance matrix and then submitted to PCA using the BMDP4M package.

The PCA isolated five components with eigenvalues greater than one; these components accounted for 92% of the variance in the original data. The five components were rotated using the normalized varimax criterion. The grand mean ERP (across all deaf and hearing Ss, all electrodes and all visual fields) and the loadings of the five components are shown in Fig. 9. Component scores were derived to assess the magnitude of the components in different ERPs. Four- and five-way analyses of variance were performed on the component scores.

The first component onset around 200 msec, peaked around 700 msec, and was sustained throughout the analysis epoch. In hearing Ss this component was largest parietally and loaded positively everywhere except at the frontal sites (electrode $F(4, 36) = 4.4$, $p < .005$). On the other hand, in deaf Ss this component was largest at the three anterior electrodes where it loaded negatively (electrode $F(4, 28) = 14.7$, $p < .00001$). Furthermore, this component was asymmetric, being more negative over the left than the right anterior regions in the deaf Ss (electrode by hemisphere $F(4, 28) = 3.6$, $p < .01$). Hence, on the average component 1 was positive in hearing Ss but negative in deaf Ss (group $F(1, 16) = 7.2$, $p < .01$); this group difference was most pronounced at the anterior electrodes (group \times electrode $F(4, 64) = 3.2$, $p < .01$).

The second component onset around 200 msec and peaked around 400 msec. In hearing Ss this component loaded negatively at the anterior electrodes and it showed a similar asymmetry for all word presentations: the left hemisphere was more negative than the right (hemisphere $F(1, 9) = 15.1$, $p < .003$). This asymmetry was largest after RVF word presentations (hemisphere \times field $F(2, 18) = 18.2$, $p < .00001$; see Fig. 10). At the posterior electrodes this component loaded positively ipsi-

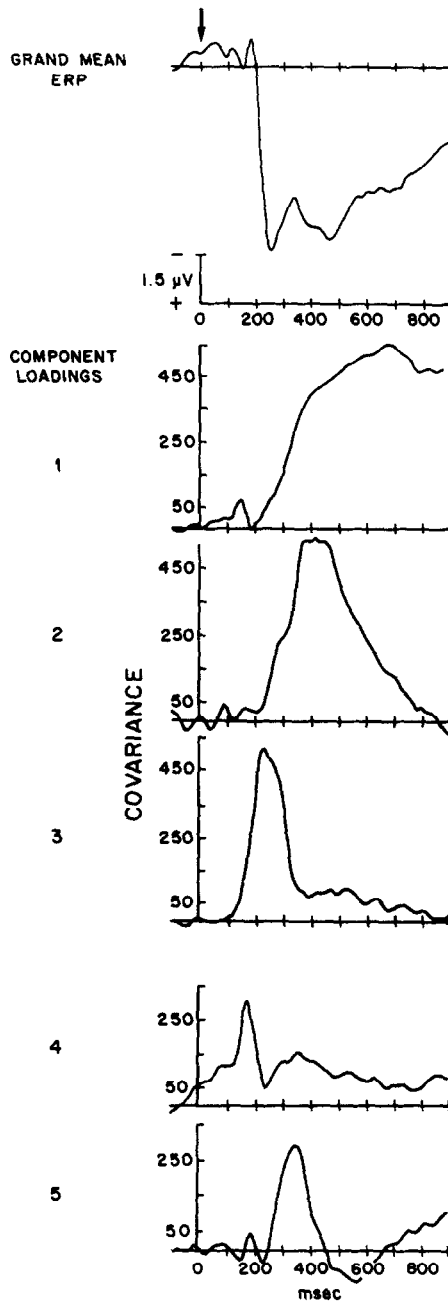


FIG. 9. The grand mean ERP, averaged across 8 deaf and 10 hearing Ss, 10 electrode positions and 3 visual field presentations, and the loadings of the five components (eigenvalues > 1) extracted by the PCA.

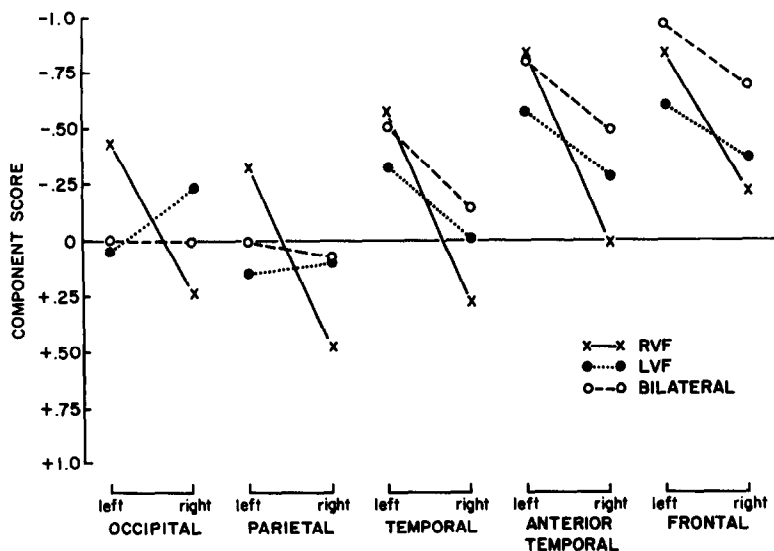


FIG. 10. Mean scores of component 2 for hearing Ss at left and right occipital, parietal, temporal, anterior temporal, and frontal electrodes following left (LVF), right (RVF), or bilateral visual field word presentations.

lateral to the field of unilateral word presentation and was symmetrical following bilateral presentations (electrode \times field \times hemisphere $F(8, 72) = 4.7, p < .0001$; see Fig. 10).

In deaf Ss component 2 was on the average positive and only loaded negatively at the frontal electrodes (electrode $F(4, 28) = 6.3, p < .0009$). It tended to be more positive from the right hemisphere (hemisphere $F(1, 7) = 6.5, p < .04$) for all visual field presentations. The group effect showing this component to be negative in hearing Ss, positive in the deaf, missed statistical significance ($F(1, 16) = 3.0, p < .10$).

The third component peaking around 250 msec was negative at the posterior electrodes and positive at the anterior electrodes for both groups (electrode $F(4, 64) = 59.6, p < .00001$). It was largest for bilateral presentations in the hearing Ss (group \times field \times electrode $F(8, 128) = 5.2, p < .00001$).

The fourth component included an early peak around 180 msec followed by a slow shift. In hearing Ss this component was more negative from the left than the right hemisphere (hemisphere $F(1, 9) = 7.9, p < .02$) especially after RVF presentations (field \times hemisphere $F(2, 18) = 3.7, p < .04$). However, at the occipital electrodes it was more negative contralateral to field of word presentation (electrode \times field \times hemisphere $F(8, 72) = 2.5, p < .01$). There were no significant main effects or interactions for this component in the deaf Ss, nor did it display any significant group differences.

The fifth component peaked between 300 and 400 msec. In hearing Ss this component loaded negatively at parietal electrodes but positively at the frontal electrodes (electrode $F(4, 36) = 3.1, p < .02$). It tended to be negative from the left and positive from the right hemisphere after both RVF and bilateral word presentations but positive in both hemispheres after LVF presentations (hemisphere \times field $F(2, 18) = 7.7, p < .003$).

In deaf Ss component 5 was more negative in the right than the left hemisphere (hemisphere $F(1, 7) = 8.3, p < .02$). This asymmetry tended to be most pronounced at the parietal and anterior electrodes (hemisphere \times electrode $F(4, 28) = 2.7, p < .05$), and it was the same for all visual field presentations (hemisphere \times visual field $F(2, 14) = 0.4, NS$). This component was more asymmetric in deaf than hearing Ss and, as shown in Fig. 11, displayed opposite patterns of hemisphere asymmetries in the two groups: it was more negative from the right than the left hemisphere in deaf Ss, but was more negative from the left than the right hemisphere of hearing Ss (group \times hemisphere $F(1, 16) = 11.0, p < .004$).

DISCUSSION

This study investigated the hypothesis that functional cerebral specialization during identification of English words would be different in congenitally deaf adults from that in normally hearing adults. Both the behavioral results and the ERPs obtained are consistent with this proposition.

Hearing and deaf Ss performed equally well in identifying words presented to the two visual fields, however, while every hearing S showed behavioral evidence of left-hemisphere specialization in the written identification of words (i.e., a RVF advantage), deaf Ss showed no consistent behavioral asymmetries. Similarly, although the ERPs from both deaf

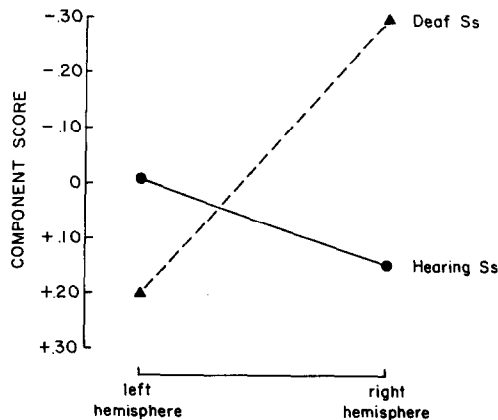


FIG. 11. Mean scores of component 5 for deaf and hearing Ss at the left- and right-hemisphere electrodes.

and hearing Ss displayed large and reliable morphological differences within and between the two hemispheres, the nature of these differences was markedly different in the two groups. In hearing Ss the early negativity over the occipital regions (N200) reflected the anatomy of the visual system (i.e., was larger contralateral to the word), while over the anterior regions it (N160) was asymmetric in the same direction regardless of position of word(s) in the visual field. The early negative components from deaf Ss did not display either of these patterns, but instead were much more heterogeneous. Moreover, the N300 response, prominent in the left parietal region of hearing Ss when words were presented to the RVF, was not observed in the left hemisphere of deaf Ss under any conditions.

Both traditional measures of the ERPs (the N410) and the PCA (component 2) also confirmed the reliability of the cerebral asymmetry beginning around 250 msec when, in every hearing S, the anterior regions of the left hemisphere were consistently more negative than the right hemisphere. Thus in hearing Ss the left hemisphere displayed a large negative-positive shift not evident over the right hemisphere. In contrast to these results deaf Ss' ERPs from the anterior regions of the left hemisphere did not display such a negative-positive shift but rather were at baseline or were characterized by a sustained *negative* shift. Area measures and the PCA (component 1) support this description of the group differences in the region from 500 to 900 msec.

While the right-hemisphere ERPs of these two groups were more similar than the left-hemisphere ERPs, deaf Ss' ERPs contained a negative peak around 330 msec at the right anterior sites that was not so prominent in the right hemisphere of hearing Ss. Although this morphological difference made it difficult to compare the two groups' ERPs directly, the PCA supported this description by identifying a component (5) in this region which was more negative in the right than the left hemisphere of deaf Ss but showed an opposite asymmetry in hearing Ss.

While the anterior ERPs from both groups were asymmetrical for all visual field presentations the two groups differed considerably in the amplitude of this asymmetry as a function of visual field of word presentation. That is, in hearing Ss this asymmetry was twice as large for RVF words as for LVF or bilaterally presented words, but in deaf Ss it was of equal magnitude for all three types of presentations. Moreover, as shown clearly in the difference ERPs, the latency of the peak asymmetry was considerably earlier in the hearing (400 msec) than in the deaf Ss (600 msec).

While the ERPs provide evidence that cerebral organization was not the same in the two groups, at this time it is unknown whether the different ERP components reflect the activity of similar processes that involve different brain regions in the two groups, or reflect the activity of different processes altogether.

However, we can propose that the ERP asymmetries observed in the hearing Ss are related to their behavioral asymmetries and reflect the activity of systems in the left hemisphere that are specialized for the language processing required to perform this task. Moreover, we will propose a few testable hypotheses concerning the nature of cerebral specialization for language and why it might be different in deaf and hearing Ss.

First we note that while the behavioral results are consistent with the interpretation of the ERPs from the hearing Ss, the behavioral results from the deaf Ss showed no evidence of functional asymmetries. Such findings are consonant with other reports of differences between ERPs and behavioral measures which have been interpreted as suggesting that these two measures reflect different aspects of the particular process being studied (Donchin, Ritter, & McCallum, 1978). It may well be that ERPs are more sensitive to functional cerebral specialization than behavioral measures since they are time-locked to the presentation of the words and thereby can index processes which occur before the behavioral response. With this caveat in mind, let us consider the results showing that the deaf Ss displayed neither the behavioral nor the ERP evidence for left hemisphere specialization observed in the hearing Ss.

If the left hemisphere is primarily specialized to perform acoustic and/or phonetic analyses, which by all indications are not performed by deaf Ss, this factor may have determined the cerebral asymmetries in the hearing Ss and may account for the different pattern of left-hemisphere activity during reading in deaf Ss. Evidence from a number of studies suggests that whereas hearing Ss perform a visual to auditory ("grapheme-phoneme") conversion on written letters and words, deaf Ss do not. For example, the errors which hearing Ss make on recall tests suggest auditory confusions (e.g., recall B rather than V) while the recall errors of deaf Ss suggest visual confusions (e.g., recall X rather than V; Conrad, 1977). This hypothesis can be tested explicitly by comparing cerebral specialization in profoundly deaf Ss who do not use speech (like the Ss in the present study) with that in hard-of-hearing, "oral" deaf Ss who are more likely to perform phonological encoding of written material (Conrad, 1977).

A related hypothesis is suggested by the studies which show that while hearing Ss appear to process grammatical morphemes (or "function" words) differently from words which make reference (or "content" words), deaf Ss do not show evidence of discriminating between these word classes (Locke, 1978). If the left hemisphere is primarily specialized for the grammatical recoding of language information (Liberman, 1974), then to the extent that the grammar of English is not salient, or has not been acquired by the deaf Ss (this is frequently the case with congenitally deaf individuals; Conrad, 1977), the left hemisphere may not mediate

reading of English. This question could be investigated by comparing cerebral specialization in deaf Ss who are familiar with the grammar of English (e.g., those who employ signed English in communication) with those whose primary form of communication is ASL (like the Ss in the present study).

While these factors may in part underlie the absence of left-hemisphere specialization in deaf Ss on this task, the question remains as to why some ERPs components were more prominent in the right than the left hemisphere in the deaf Ss. Perhaps the well-documented specialization of the right hemisphere for certain visuo-perceptual skills also includes the analysis of language information which is visual and not phonetically based. Some support for this notion is suggested from studies reporting different patterns of cerebral specialization for the Japanese languages Kana and Kanji (Sasanuma, Itoh, Mori, & Kobayashi, 1977). While left-hemisphere specialization has been documented for the former, which is phonetically based, some studies suggest that the right hemisphere mediates the ideographic script, Kanji. However, there is contradictory evidence on this point.

Bearing on this and other hypotheses will be ERP and behavioral results from studies employing ASL. Since this language requires considerable visuospatial analysis, and is at the same time highly grammatical, but not phonetic (Klima & Bellugi, 1979), studies of cerebral specialization during the processing of ASL hold the promise of clarifying the present results, and their relation to more general questions concerning the nature of hemispheric specialization.

We also observed a large difference in ERPs from deaf and hearing Ss which did not seem to be related to lateral functional specialization. The slow positive shift beginning around 500 msec over temporal and frontal regions was much larger in hearing than deaf Ss over both the left and the right hemispheres. While future research is required to investigate the significance of this symmetrical shift in the ERPs and the group differences it displays, it may reflect general (i.e., not language specific) reorganization of these regions in Ss who have been deprived of auditory stimulation since birth. In fact, we have observed marked alterations in the ERPs to simple, nonlanguage visual stimuli recorded over frontal and temporal regions in congenitally deaf Ss, and have suggested that these brain areas, which normally subserve audition and speech, may have become organized to process visual information in congenitally deaf Ss (Neville, Schmidt and Kutas, submitted).

In summary, these results demonstrate that during this reading task both inter- and intra-hemispheric relations were different in normally hearing and congenitally deaf Ss. Further studies are required to clarify the factors that determined these differences. However, the results suggest that the normal maturational course which generally ends with the

left hemisphere specialized for reading can be altered when language acquisition is abnormal.

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