Event-Related Potential Studies of Cerebral Specialization during Reading

A Comparison of Normally Hearing and Congenitally Deaf Adults[a]

HELEN J. NEVILLE,[b] MARTA KUTAS,[c]
AND ALBERT SCHMIDT[b]

[b]*The Salk Institute*
[c]*University of California, San Diego*
La Jolla, California 02037

While several different lines of research attest to the different functional specializations of the two cerebral hemispheres in the mature human, little is known about the ontogeny of this aspect of cerebral organization. The research reported here has been designed to investigate the role of language acquisition in the course of neural development whereby the left cerebral hemisphere becomes specialized for speech and language functions and the right hemisphere for certain nonlanguage perceptual abilities. Our approach is based on the assumption that if the nature of language acquisition is an important variable in the development of cerebral organization, then people with different language experiences should display different functional hemispheric specializations. To test this hypothesis, we compared the morphologies and scalp distributions of the event-related potentials (ERPs) recorded during a word reading task in two groups of subjects who have had vastly different language experiences: normally hearing people who first acquired the vocabulary and grammar of English through the auditory modality, and congenitally deaf people who have learned to read English through picture-grapheme association in the visual modality.

While electrophysiological manifestations of the different functional specializations of the two hemispheres at the scalp have remained fairly elusive, the various critiques of this type of research have indicated much room for methodological and analytic improvement (Galambos *et al.*, 1975; Friedman *et al.*, 1975; Donchin *et al.*, 1977; Hillyard and Woods, 1979; Neville, 1980). Our investigation of hemispheric specialization during reading was therefore designed to circumvent the methodological shortcomings of previous research of this type (Neville *et al.*, 1982a).

METHODS AND PROCEDURES

First, in order to ensure active participation by the subject and to provide behavioral evidence to aid in the functional interpretation of any obtained ERP asymmetries, subjects were required to identify in writing different words presented to

[a]This work was supported by NIH Research Grant No. NS14365 and the Alfred P. Sloan Foundation. Marta Kutas is supported by Research Scientist Development Award USPHS 1 K02 MH 00322.02. We are grateful to Steven A. Hillyard for critical comments and helpful discussions.

the two visual fields. Second, to avoid biases associated with direction of scanning or with ease of identifying words which begin close to the fovea (right visual field) *versus* those which end close to the fovea (left visual field), words were presented in vertical orientation. Third, central fixation was monitored by requiring accurate discrimination of a colon (:) from a semicolon (;) presented in the center of the display. Fourth, in view of recent reports of reliable asymmetries in relatively low frequency, long-latency ERP components (Desmedt, 1977; Kutas and Hillyard, 1980; Neville, 1980), the EEG was amplified with a 0.01 Hz low frequency cutoff. Fifth, in an attempt to reduce the amplitude of sensory evoked ("exogenous") ERP components (*i.e.*, the "flash" EP) in relation to those associated with linguistic processing, the words were white and were presented on a darkened video screen. Finally, recordings were made across the entire scalp from several different pairs of electrodes over homologous frontal (F7, F8), anterior temporal [one-half of the distance between F7(8) and T3(4)], temporal (33% of the interaural distance lateral to Cz), parietal (P3, P4) and occipital (O1, O2) regions of the left and right hemispheres. Recordings from all the lateral electrodes and from beneath the left eye were referred to linked mastoids. Electrical activity was amplified with a bandpass of 0.01–100 Hz, recorded on FM tape and analyzed offline on a PDP 11/45 computer.

Subjects. The subjects were ten normally hearing and eight congenitally deaf adults. All subjects were right-handed.

Stimuli. The stimuli were four letter English nouns randomly presented for 100 ms, 1.6 degrees to the left or right of fixation. All subjects received six practice trials, thirty unilateral right, thirty unilateral left and thirty bilateral word presentations (*i.e.*, two *different* words), all randomly intermixed.

RESULTS

The hearing subjects demonstrated reliable behavioral evidence for left hemisphere specialization by correctly identifying significantly more words presented to the right than to the left visual field. FIGURE 1a demonstrates that this asymmetry was observed in every subject after both unilateral and bilateral word presentations; points above the diagonal indicate better identification after right visual field presentations [$F(1,9) = 93.0, p < 0.001$]. In parallel with their behavioral data, the hearing subjects' ERPs also displayed large and consistent lateral asymmetries. ERPs from the occipital regions primarily reflected where in the visual field a word had been presented. On the other hand, ERPs from more anterior electrodes displayed large, reliable asymmetries which occurred in the same direction regardless of the visual field of word presentation. The most striking such asymmetry was in the negativity in the 300–500 ms region of the ERPs recorded over the temporal and frontal sites. FIGURE 1b demonstrates that this negativity, which was maximal around 410 ms, was consistently larger from the left hemisphere than from the right hemisphere whether words were presented to the right visual field, the left visual field or bilaterally. ANOVAs of both the peak negativity and of the area between 300 and 500 ms relative to a 100 ms prestimulus baseline indicated that the N410 was significantly larger over the left hemisphere than over the right hemisphere for each type of visual field presentation at the frontal, anterior temporal and temporal sites [hemisphere effect $F(1,9)$ base-peak = 38.4, area = 40.0, both $p < 0.0001$].

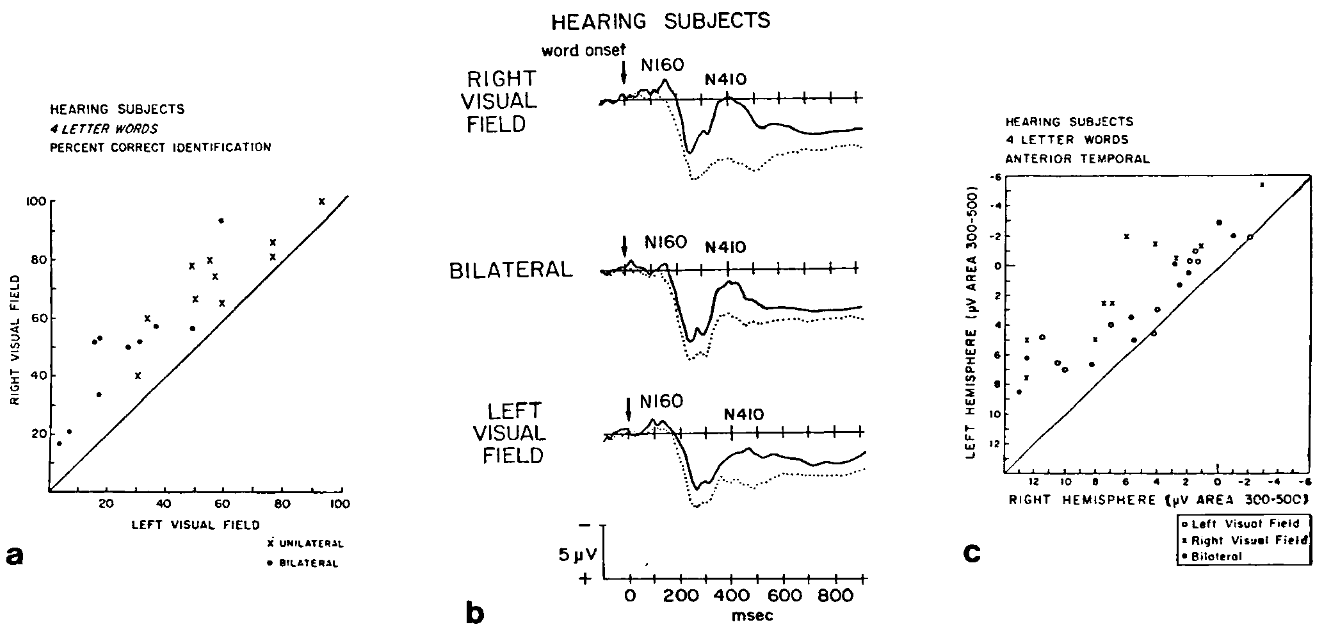

FIGURE 1. (a) Percent correct word identification for each hearing subject. Points fall above the diagonal if accuracy was better after right visual field (left hemisphere) presentations. (b) ERPs averaged over all ten hearing subjects from left (—) and right (· · ·) anterior temporal electrodes during right, bilateral and left visual field word presentations. (c) Amplitude of N410 for each subject after words were presented to the left, right or bilateral visual fields. Points fall above the diagonal if the amplitude was greater from the left than from the right anterior temporal region.

The scatter diagram in FIGURE 1c underscores the consistency of this asymmetry in the individual subjects; the 300–500 ms region was more negative from the left than from the right anterior temporal locations in every subject after right visual field and bilateral word presentations and in eight of ten subjects after left visual field presentations. Moreover, FIGURES 1b and 1c show that the difference between the two hemispheres in the region of the N410 was greater when identification of words was best, *i.e.*, after unilateral right visual field presentations [hemisphere by field interaction $F(2,18)$ base-peak = 9.3, area = 12.4, both $p < 0.001$].

Both the behavioral and ERP results from deaf subjects were markedly different from those of hearing subjects, although the overall accuracy of the deaf subjects was equal to that of the hearing subjects (see FIGURE 2a). Thus, the deaf subjects showed no behavioral asymmetry—left visual field and right visual field scores were equal [group by visual field $F(1,16) = 14.7$, $p < 0.001$]. Similarly, while the general morphology of ERPs from the posterior electrodes of the deaf subjects was similar to that of hearing subjects, the pattern of lateral asymmetries was different. In particular, in contrast to the hearing subjects' ERPs, the N200 at the occipital sites of deaf subjects showed a right hemisphere dominance: its amplitude was larger from the right than from the left hemisphere after both left visual field and bilateral word presentations.

At the anterior sites, the ERPs from deaf subjects differed from those of the hearing subjects not only in lateral distribution but in morphology as well (see FIGURE 2b). In fact, the morphological differences in the ERPs between the two groups rendered a direct comparison quite difficult. Nonetheless, a comparison revealed that the negative-positive shift in the left anterior temporal region of the hearing subjects was not evident in ERPs from the left hemisphere of deaf subjects. Thus, while the area from 500–900 ms was positive in hearing subjects (mean $+3.0\ \mu V$), it was at baseline or negative in deaf subjects (mean $-1.7\ \mu V$; group effect $p < 0.001$).

While the ERPs from the right hemispheres of the two groups were more similar, the deaf subjects displayed a somewhat more prominent, earlier negativity (marked by the asterisk in FIGURE 2b) than did the hearing subjects. The peak-to-peak amplitude between the most negative point between 300–500 ms and the subsequent positivity was greater from the left hemisphere than from the right hemisphere of hearing subjects, but was greater from the right than from the left hemisphere of deaf subjects [hemisphere by group $F(1,16) = 8.2$, $p < 0.01$]. The consistency of this asymmetry in the deaf subjects is depicted in the scatter plot in FIGURE 2c.

ERPs from both hemispheres displayed group differences in the slow shift at the termination of the analysis epoch. The area from 700–900 ms was significantly more positive from left and right anterior leads in hearing subjects than in deaf subjects [group $F(1,16) = 9.1$, $p < 0.008$].

While both the N410 in the left hemisphere of hearing subjects' ERPs and the negative peak in the right hemisphere of deaf subjects were initially negative-going, they were often positive with respect to the prestimulus baseline. In order to assess the possibility that these components may have been modulated by the slow shifts that were sustained until at least 900 ms, a principal components analysis (PCA) was applied to the data. The PCA (more fully described in Neville *et al.*, 1982b) isolated a component with an onset at 200 ms which was sustained throughout the epoch. This component was positive in hearing subjects but negative in deaf subjects [group $F(1,16) = 7.2$, $p < 0.01$]. The PCA also isolated a component peaking between 300 and 400 ms that displayed opposite patterns of asymmetry in the two groups: it was more negative from the left than from the right hemisphere of the hearing subjects but more negative from the right than from the left hemisphere of deaf subjects [group by hemisphere $F(1,16) = 11.0$, $p < 0.004$].

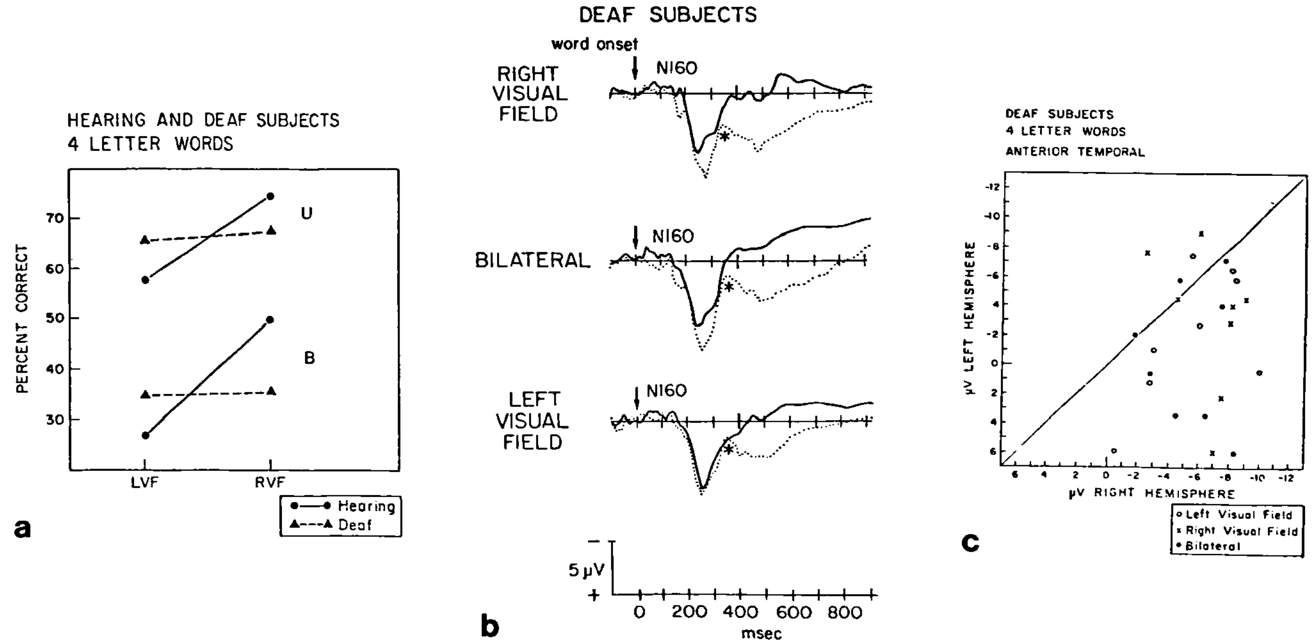

FIGURE 2. (a) Percent accuracy of word identification after left and right visual field presentations (U = Unilateral; B = Bilateral) by hearing (—) and deaf (---) subjects. (b) ERPs averaged over all eight deaf subjects from left (—) and right (· · ·) anterior temporal electrodes during right, bilateral and left visual field word presentations. (c) Peak-to-peak amplitude of negative-positive shift for each deaf subject after left, right or bilateral visual field word presentations. Points fall below the diagonal if the right anterior temporal amplitude was greater than the left.

DISCUSSION

Every hearing subject displayed behavioral evidence of left hemisphere specialization as well as a negative (410 ms)–positive shift that was more pronounced in ERPs from the left than from the right anterior temporal regions. Thus the N410 complex may reflect aspects of the specialized role of the left hemisphere in this reading task. By contrast neither the behavioral data nor the ERPs from deaf subjects displayed a similar pattern. Instead a larger negative-positive shift occurred in the right anterior-temporal regions of the deaf subjects. Although it is still unknown whether these events reflect similar processes lateralized to opposite hemispheres in the two groups or different processes altogether, these different lateral asymmetries for deaf and hearing subjects suggest that functional cerebral specialization during reading is indeed different in the two groups.

Testable hypotheses of factors that may have determined the different patterns of asymmetries in the hearing and deaf subjects in this reading task include: (a) English is not a phonetically based language for deaf subjects; perhaps the left hemisphere is specialized for phonology while all visually based languages may be mediated by the right hemisphere, (b) English is a second language for deaf subjects; some evidence suggests that second languages involve the right hemisphere more than does the primary language, (c) many deaf subjects do not fully learn the structure (grammar) of English. If the left hemisphere is predisposed to specialize for the acquisition of formal (grammatical) language, this may be why we do not see evidence of left hemisphere specialization for English in deaf subjects. Indeed, methods of teaching reading by word-picture association may encourage right hemisphere specialization.

We also observed differences in the slow shift that lasted until the end of the ERP epoch. While the functional significance of this shift remains to be determined, it may reflect general reorganization of these regions in subjects who have been deprived of auditory stimulation since birth. We have observed evidence consistent with this interpretation in other experiments (Neville *et al.*, 1983).

In summary, results from this study demonstrate that (1) in paradigms which demand specialized language processing, ERPs are sensitive to aspects of cerebral organization both within and between the hemispheres and (2) in these paradigms ERPs can be used to study the role of experience in the development of the functional organization of the human brain.

REFERENCES

DESMEDT, J. E. 1977. Active touch exploration of extrapersonal space elicits specific electrogenesis in the right-handed man. Proc. Nat. Acad. Sci. U.S.A. **74:** 4037–4040.

DONCHIN, E., M. KUTAS & G. MCCARTHY. 1977. Electrocortical indices of hemispheric utilization. *In* Lateralization in the Nervous System. S. Harnad, R. W. Doty, L. Goldstein, J. Jaynes & G. Krauthamer, Eds.: Academic Press. New York.

FRIEDMAN, D., R. SIMSON, W. RITTER & I. RAPIN. 1975. Cortical evoked potentials elicited by real speech words and human sounds. Electroencephalogr. Clin. Neurophysiol. **38:** 13–19.

GALAMBOS, R., P. BENSON, T. S. SMITH, C. SCHULMAN-GALAMBOS & H. OSIER. 1975. On hemispheric differences in evoked potentials to speech stimuli. Electroencephalogr. Clin. Neurophysiol. **39:** 279–283.

HILLYARD, S. A. & D. L. WOODS. 1979. Electrophysiological analysis of human brain function. *In* Handbook of Behavioral Neurobiology, vol. 2. M. S. Gazzaniga, Ed.: Plenum. New York. 345–378.

KUTAS, M. & S. A. HILLYARD. 1980. Reading between the lines: Event-related brain potentials during natural sentence processing. Brain and Language **11:** 354–373.

NEVILLE, H. 1980. Event-related potentials in neuropsychological studies of language. Brain and Language **11:** 300–318.
NEVILLE, H. J., M. KUTAS & A. SCHMIDT. 1982a. Event-related potential studies of cerebral specialization during reading. I: Studies of normal adults. Brain and Language **16:** 300–315.
NEVILLE, H. J., M. KUTAS & A. SCHMIDT. 1982b. Event-related potential studies of cerebral specialization during reading. II: Studies of congenitally deaf adults. Brain and Language **16:** 316–337.
NEVILLE, H. J., A. SCHMIDT & M. KUTAS. 1983. Altered visual evoked potentials in congenitally deaf adults. Brain Res. **266:** 127–132.