JADARA

Volume 23
Number 2 *10/01/1989*

Article 5

September 2019

Brain-Behavior Relationships in Deaf Children: The Gallaudet Neurobehavioral Project

Anthony B. Wolff
Gallaudet Research Institute

Betsy L. Kammerer
The Children's Hospital – Boston and Department of Psychiatry, Harvard Medical School

Judith K. Gardner
The Children's Hospital – Boston and Department of Psychiatry, Harvard Medical School

Robert W. Thatcher
Applied Neurosciences Laboratory- University of Maryland—Eastern Shore

BRAIN-BEHAVIOR RELATIONSHIPS IN DEAF CHILDREN: THE GALLAUDET NEUROBEHAVIORAL PROJECT

Anthony B. Wolff, Ph.D.
Gallaudet Research Institute

Betsy L. Kammerer, Ph.D. and Judith K. Gardner, Ph.D.
The Children's Hospital, Boston and
Department of Psychiatry, Harvard Medical School
and

Robert W. Thatcher, Ph.D.
Applied Neurosciences Laboratory
University of Maryland—Eastern Shore

Introduction

The effect of prelingual deafness on brain development and function has historically been a subject of considerable speculation but little research. While numerous studies have examined various aspects of cognitive functioning among deaf individuals (see Martin, 1985, for a review), very few of these have simultaneously utilized physiological measures of brain function. A few other studies have examined physiological indices of cerebral function in deaf individuals (e.g., Neville, Schmidt, & Kutas, 1983; Samar, 1983; Hughs, 1971), but these have generally not related the physiological findings to cognitive, educational, or social/emotional aspects of functioning.

Interest in this area derives from several directions, one being the general question of whether the absence or attenuation of auditory experience, and its concomitant linguistic and other adaptations, may give rise to the development of atypical functional specialization in various areas of cerebral cortex. Various lines of research with animals have demonstrated neural changes as a consequence of early sensory deprivation both in the visual (Globus, Rosenzweig, Bennett, & Diamond, 1973; Greenough, Black, & Wallace, 1987) and auditory (Rubel, 1984) systems.

A second question stems from the relatively high prevalence of causes of deafness that are also potentially injurious to the central nervous system. This contributes to the existence of an unusually high proportion of individuals with varying degrees of neurological dysfunction among the deaf population (Vernon, 1968; Wolff & Harkins, 1986; Brown, 1986).

A third concern is a practical one, namely, the need among education and mental health professionals for valid, useful techniques to measure cognitive and neuropsychological function in the deaf population. Very few instruments have been adapted for use with deaf subjects (see Zieziula, 1982, for a review), although in clinical practice a number of instruments are regularly employed (Vernon & Oettinger, 1981; Orr, DeMatteo, Heller, Lee & Nguyen, 1987). To the extent that deafness results in modified cerebral functioning, the interpretation of standard neuropsychological instruments needs to be altered. The lack of appropriate deaf norms for many instruments and the linguistic incompatibility of many English-based instruments with the communication needs of deaf individuals, added to a lack of understanding of basic developmental neurological processes in deaf children, combine to frustrate many of the best efforts of applied workers in the field.

This paper describes one project designed to examine cerebral function and cognitive processing in prelingually deaf children and adolescents, with the intention of examining these underlying issues. This project has two components, which we describe separately: First, utilizing computer assisted electroencephalography (EEG), we developed a set of topographic maps that contrast certain aspects of the cerebral cortical development of deaf and hearing children. Second, we administered a carefully selected battery of neuropsychological tests to each deaf child. The intention was to study (1) the effect of deafness *per se* on cerebral function, (2) the influence of various causes of deafness on cerebral function, and (3) the relationship between physiological variables and cognitive measures. Further, it was hoped that a contribution would be made to the development of a neuropsychological test battery for deaf children and adolescents.

Subjects

One hundred severely to profoundly prelingually deaf children, ages 6 to 16, were selected from total-communication-oriented educational settings in the Washington-Baltimore area. We specifically recruited for children whose primary means of communication was sign language, and while this criterion was generally met, considerable variability occurred in this regard, with some subjects clearly functioning better orally than others.

In addition to the deaf subjects, a group of 93 hearing children were selected from the data base of the University of Maryland Applied Neurosciences Laboratory. Data available for these subjects included EEG and IQ testing, as well as a variety of background variables. None suffered from known handicaps or neurological pathologies. They were matched with the deaf subjects on performance IQ and age.

Because of our interest in the cause of deafness variable, an attempt was made to include deaf subjects only with known etiologies, and these subjects were then assigned to one of two groups: (1) genetically deaf, for those children with documented familial deafness or (2) neurologically-at-risk deaf (NAR), for those whose deafness had resulted from maternal rubella (n=22), other infections (n=2), Rh factor incompatibility (n=2), Mondini-Alexander syndrome (n=2), head trauma (n=2), perinatal anoxia (n=2), and pregnancy complication (n=1). Despite these classification efforts, the medical histories of some subjects proved to be inconclusive and these children were therefore placed in a third category: unknown etiology. Children with significant handicaps other than deafness, learning disabilities, or behavior problems were excluded. Ultimately, data were collected from 93 subjects, with a mean age of 12.29 years, and a mean pure tone average hearing loss in the better ear of 95 dB SPL. The group consisted of 37 subjects with genetic deafness (19 male, 18 female), 42 with NAR deafness (29 male, 13 female), and 14 with unknown etiology (8 male, 6 female). This method of grouping allowed some degree of isolation of cerebral effects of deafness *per se* from possible other effects attributable to organic insult and related adaptations.

EEG Topographic Mapping

Procedure

Most of the available brain imaging techniques were inappropriate for our purposes, which demanded a technique that was both free of risk and informative regarding dynamic cortical function. Topographic brain mapping, a technique based on quantitative analysis of EEG data, was selected as the best approach. This technique, pioneered as "neurometrics" by John and co-workers (John et. al., 1977), has excellent temporal resolution – detecting changes in brain activity in time intervals as small as one-one-hundredth of a second in our implementation – and hence can reveal various aspects of dynamic function. Spatial resolution, which determines the ability to distinguish differences in activity at different cerebral locations, is sufficient to distinguish among key regions of the cortex. Finally, network properties, that is, inter-relationships among cortical regions, can be explored.

EEG data were collected from each subject following standard technique, using the International 10-20 system. Each subject was seated in a dimly lit sound-proof booth and asked to close his or her eyes. One minute of eyes-closed EEG was then collected, using a mini-computer-based data acquisition system. EEG coherence, phase, and power were calculated for all relevant electrodes or electrode pairs in the usual delta, theta, alpha and beta frequency bands. *Coherence* is similar to a correlation coefficient in the frequency domain (Nunez, 1981) and represents the amount of waveshape similarity between the patterns of activity at two electrodes. Coherence is thus a measure of the degree to which two areas of cerebral cortex are functionally coupled (Saltzberg, 1982). *Phase,* which also can be interpreted as a measure of the coupling between two cortical areas (Thatcher et al, 1986; Thatcher et al, 1987), represents the time shift between activity at two electrodes (Nunez, 1981). *Power* is computed for each electrode, and corresponds to the synchrony of underlying neural dipole (electric) generators at the electrode (Nunez, 1981). Power decreases as a function of increasing age in children (Matousek & Petersen, 1973), and it thus can be viewed as a measure of maturation. It should be clarified that because these EEG data were collected during an awake but inactive state of arousal, they are viewed as reflecting cortical network properties with implications for readiness for processing and developmental status. These data may or may not reflect the nature of active processes.

Coherence, phase and power variables were submitted to a series of multivariate analyses of covariance (using age and IQ as covariates) in order to develop topographic maps which reveal differences between deaf and hearing subjects. A more complete description of these techniques and results can be found in Wolff and Thatcher (1990, in press). Also, factor analytic results in which these EEG findings are related to neuropsychological test findings can be found in the Appendix. The statistical analyses discussed here (both on EEG and neuropsychological data), were designed to remove possible development effects. Thus, differences in these measures as a function of subject age are not considered. Rather, the focus is on differences between genetically deaf, neurologically at risk deaf, and hearing groups of subjects without respect to age.

Results

Deaf children had higher coherence in the left temporo-frontal area, which is one of the classic areas associated with linguistic functioning. Higher coherence in deaf children was also observed in bilateral frontal cortex, which serves numerous cognitive functions including abstraction, concept formation, planning, and impulse regulation (Stuss & Benson, 1986). Since coherence is an index of the degree of inter-regional coupling in the cerebral cortex, it can be interpreted as relating to the degree of interneuronal differentiation present, which in turn is related to maturation and specialization of function (Giannitrapani, 1985 [p. 14]). These results suggest that deaf children tend to have less differentiation in left temporo-frontal and bilateral frontal regions than hearing children. Since a variety of animal studies confirm that lack of stimulation affects the development of underlying brain structures, the relatively lower differentiation in the language-related left hemispheric area may represent a lack of oral/auditory linguistic experience in our deaf subjects. This may in turn give rise to a difference in frontal lobe function. However, it should be emphasized that the functional implications of these detected differences are unclear.

A third area of higher coherence among deaf subjects was in the posterior, principally occipito-parietal region, which is associated with visual processing. This may represent not a deficit among the deaf subjects, but rather it may be evidence of heavy utilization, or in neural terms, heavy synaptic driving, of the visual system. This interpretation is reinforced by results of the phase measure, to be discussed below. A finding that deaf subjects manifest electrophysiological evidence of heavy utilization of the visual system is consistent with the view that persons with sensory deprivation in one modality develop compensatory function in another modality. This has been suggested by previous research with deaf subjects using visual evoked potentials (Neville, Schmidt & Kutas, 1983; Samar, 1983). Another coherence finding suggestive of neural compensation was observed only in the genetically deaf subjects, namely the presence of lower coherence in the right anterior cortex (fronto-central and fronto-temporal). This finding suggests greater interneuronal differentiation for these genetically deaf subjects than for hearing subjects in those regions, implying some form of adaptive compensatory function. In general there is higher coherence, as well as lack of areas with lower coherence, in the NAR group as compared with the genetic group. This suggests overall that the NAR deaf children differ more from hearing children than do genetically deaf children in terms of neural development and function.

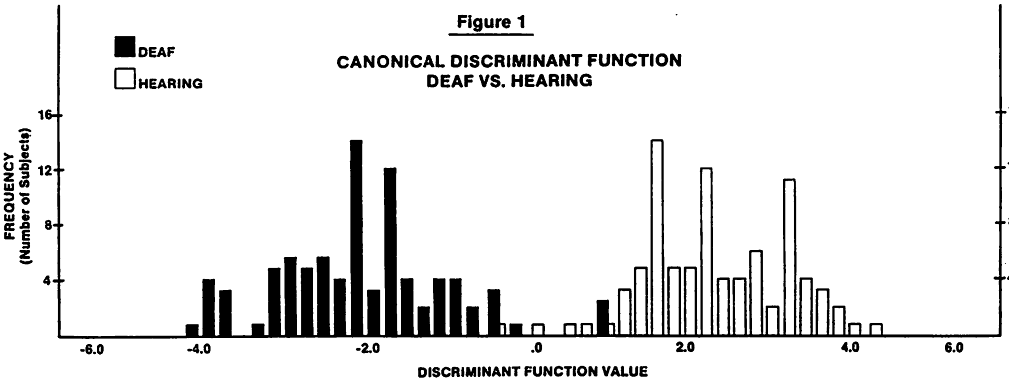
Phase results were generally consistent with the coherence findings, revealing lower phase (less differentiation) in the left hemisphere and higher phase (greater differentiation suggestive of neural compensation) in the right hemisphere for both groups of deaf subjects in comparison to hearing children. A significant way in which phase differed from coherence was the presence of high phase in the right occipital-temporal area in both deaf groups, which is associated with visual processing. This may again reflect some aspect of compensatory functioning in the deaf subjects.

Analysis of power results reveals that deaf children manifested higher total power, consistent with norms for younger hearing children, in the frontal cortex than did hearing children. This finding is consistent with results observed in coherence, confirming that in some respect these deaf subjects manifested differences from hearing subjects in the pattern of activity in frontal cortex. This observation did not vary greatly in relation to cause of deafness.

Discriminant function analysis, using 42

Figure 1

CANONICAL DISCRIMINANT FUNCTION DEAF VS. HEARING



coherence, phase and power variables selected for significant predictive power, was highly effective in dichotomizing deaf and hearing subjects (Figure 1), with a correct classification rate of 97.4% (Chi-squared(41) =233.72, $p < .00005$). Similarly, using 14 coherence and phase variables, discriminant analysis classified subjects as either genetically or NAR deaf (Figure 2) with an accuracy of 81.5% (Chi-squared (15)=29.65; $p < .009$).

Neuropsychological Testing

Method

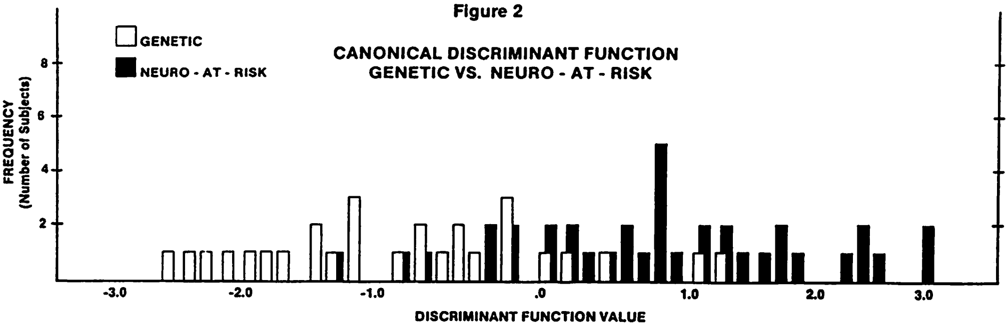
The primary purposes of this part of the project were (1) to describe basic cognitive processes in deaf subjects and (2) to develop an appropriate battery for evaluation of deaf children and adolescents. Therefore, complete background data were gathered to determine variables relevant to clinical findings. First, medical and developmental history was obtained to assess subjects' status in critical areas of general development. Second, teacher rating scales were obtained to determine subjects' functioning in academic settings. The neuropsychological tests were administered by trained research assistants who were fluent in ASL and supervised by a clinical psychologist (ABW).

Tasks were selected in which linguistic demands would not bias against deaf subjects, and were either non-verbal or required very minimal sign competence. The battery was also selected to reflect possible deaf-hearing differences in neuropsychological functioning with emphasis on broad-based cognitive tasks and specific measures of perceptual, motor, temporo-sequential (linguistic and visual) and organizational skills. These tests were utilized in this project primarily to assess function and process rather than for cortical localization, since specific, focal neurological disorder or illness was not postulated for this population. The test battery included the following:

- Performance WISC-R
- Rey Auditory-Verbal Learning Test
- Hiskey-Nebraska Visual Attention Span subtest
- Knox Cubes
- Trail-Making A & B
- Stroop Color-Word Interference Test

Figure 2

CANONICAL DISCRIMINANT FUNCTION GENETIC VS. NEURO - AT - RISK



Rey-Osterrieth Complex Figure, copy and recall
Developmental Test of Visual-Motor Integration
Benton Line Orientation Test
Mooney Closure Faces
Timed Motor Examination
Stressed Gaits
Purdue Pegboard
Lateral Dominance Examination
Language Proficiency Rating Scale
Conners Teacher Questionnaire
Meadow-Kendall Social Emotional Inventory

For all the neuropsychological battery except the WISC-R and Hiskey VAS subtest, the results presented below describe differences between deaf and hearing subjects based on *hearing* norms. These data must be interpreted with caution due to the lack of availability of deaf norms. For the clinician, however, the comparison to hearing norms (Table 2) does provide a beginning understanding of appropriate expectations for genetic and NAR deaf subjects on these tests. In other words, on tests where deaf subjects do not differ from hearing norms, the published norms may be reasonably appropriate for deaf subjects with cautious application. For other tests, when deaf subjects differ from hearing norms, the present results may provide some preliminary normative guidelines for use with deaf subjects.

As on the EEG data, statistical analyses removed age effects, since group differences rather than developmental effects were the focus of the study. Sex effects were not directly assessed.

Results

The results of the neuropsychological test battery are shown in Tables 1 through 4. Deaf subjects' scores were compared with available norms using T-tests, except as otherwise noted.

On the WISC-R (Wechsler, 1974), as shown in Table 1, genetically deaf subjects had a mean Performance IQ of 112.51 and the NAR deaf had a mean Performance IQ of 100.29. This mean for the genetically deaf group is significantly different from the expected mean but the mean for the NAR deaf group does not differ from the expected mean. Genetically deaf subjects attained scaled scores significantly above the normative means in all five WISC-R subtests administered. This finding supports the generally accepted view that genetically deaf children experience considerable advantage over NAR deaf children; previous researchers have also found Performance IQ among genetically deaf children to be higher than the hearing norm (Sisco

TABLE 1

WISC-R PERFORMANCE IQ AND SUBTEST SCALED SCORES
(Scores are based on norms developed for deaf subjects (Sisco & Anderson, 1980))

VARIABLE	HEREDITARY M (SD)	HEREDITARY p<	AT-RISK M (SD)	AT-RISK p<
Picture Completion	11.05 (2.90)	.05	9.62 (3.04)	NS
Picture Arrangement	12.60 (3.19)	.001	10.71 (3.58)	NS
Block Design	11.70 (3.23)	.01	9.98 (3.13)	NS
Object Assembly	11.70 (3.82)	.01	9.86 (3.53)	NS
Coding	12.19 (3.17)	.001	10.10 (2.92)	NS
WISC-R Performance IQ	112.57 (15.80)	.001	100.29 (17.53)	NS

& Anderson, 1980). Since key aspects of the Performance WISC-R rely heavily on visual processing, one could speculate that the advantage found here for genetically deaf children may be related to the compensatory functioning observed in coherence and phase, as discussed above.

Given postulated differences between deaf and hearing subjects on temporo-sequential skills, both linguistic and non-linguistic tasks were administered in this area. On our sign language adaptation of the Rey Auditory-Verbal Learning Test (Taylor, 1959) deaf subjects performed significantly below hearing norms on all five learning trials, as can be seen in Table 2. On this test subjects are required to immediately recall 15 signs (in citation form), with five trials to measure rate of learning. This task demands focused attention as well as recall ability. Because the test was entirely administered in sign language, there was no reason inherent in the procedure for the deaf subjects to perform below hearing norms. This result therefore may suggest difficulty with immediate recall of non-contextual material, but the fact that the norms for this instrument are derived with French children demands cautious interpretation. Further investigation of the ability to categorize and sequence similar signed items should clarify these results.

Another measure of immediate recall using pictorial rather than signed stimuli was the Visual Attention Span subtest of the Hiskey Nebraska

TABLE 2

SELECTED NEUROPSYCHOLOGICAL TEST SCORES

(All means are z-scores unless otherwise noted. P-values are based on t-tests comparing subjects' scores to published hearing norms, unless otherwise noted.)

VARIABLE	HEREDITARY		AT-RISK	
	M (SD)	p<	M (SD)	p<
Rey Auditory Verbal Learning Test Trial 1	- .69 (1.45)	.001	-1.44 (1.44)	.001
Rey Auditory Verbal Learning Test Trial 2	- .91 (1.85)	.001	-1.53 (1.52)	.001
Rey Auditory Verbal Learning Test Trial 3	-1.01 (2.03)	.001	-2.38 (1.95)	.001
Rey Auditory Verbal Learning Test Trial 4	-1.22 (2.37)	.001	-2.18 (2.38)	.001
Rey Auditory Verbal Learning Test Trial 5	-1.79 (4.03)	.001	-2.65 (3.62)	.001
Rey Auditory Verbal Learning Test Total	-1.11 (1.87)	.001	-2.02 (1.73)	.001
Hiskey Visual Attention Span Subtest	.78 (2.37)	.001	- .42 (2.22)	.01
Knox Cubes	.72 (2.20)	.001	- .20 (2.27)	NS
Trailmaking Part A	.10 (1.21)	NS	-1.38 (2.73)	.001
Trailmaking Part B	.13 (1.11)	NS	-1.06 (2.51)	.001
Stroop Test — Word Condition	- .95 (1.08)	.001	-1.45 (.87)	.001

TABLE 2 (continued)

Stroop Test — Color Condition	- .67 (1.07)	.001	-1.13 (.94)	.001
Stroop Test Color — Word Condition	- .30 (1.01)	NS	- .70 (.86)	.001
Stroop Test — Interference Score	.39 (.91)	.05	.38 (.73)	.02
Rey Osterrieth Figure — Copy	.55 (.942)	.01	- .97 (1.18)	.001
Rey Osterrieth Figure — Recall	- .34 (.88)	NS	- .29 (.75)	NS
Benton Line Orientation Test	- .38 (1.24)	.05	-1.32 (1.55)	.001
Developmental Test of Visual Motor Integration	- .45 (1.60)	.001	-1.27 (1.30)	.001
TIMED MOTOR EXAMINATION				
Non-Preferred Foot Tap	2.42 (1.73)	.001	1.33 (1.37)	.01
Non-Preferred Heel-Toe Alternation	.62 (1.50)	.01	.05 (1.45)	NS
Non-Preferred Hand Pat	2.78 (3.08)	.001	1.16 (1.59)	.001
Non-Preferred Hand Pronation/Supination	.635 (2.37)	.01	.33 (.99)	.05
Non-Preferred Hand Finger Repetition	- .32 (1.25)	NS	.84 (1.74)	.001
Non-Preferred Hand Finger Sequencing	-.015 (1.27)	NS	.01 (1.43)	NS
Preferred Foot Tap	2.38 (1.76)	.001	- .39 (2.06)	.05
Preferred Heel-Toe Alternation	.612 (1.41)	.01	.115 (1.23)	NS
Preferred Hand Pat	2.62 (3.39)	.001	.77 (1.69)	.001
Preferred Hand Pronation/Supination	- .21 (1.21)	NS	- .29 (.76)	NS
Preferred Hand Finger Repetition	.29 (1.09)	NS	.18 (1.99)	NS
Preferred Hand Finger Sequencing	.08 (1.23)	NS	.016 (1.09)	NS
Purdue Pegboard Preferred Hand	- .31 (1.26)	.05	.17 (1.36)	NS
Purdue Pegboard Non-Preferred Hand	- .13 (1.12)	NS	.12 (1.37)	NS

(Hiskey, 1941). On this task subjects must recall sequences of pictures following brief presentation. Using deaf norms, NAR deaf children performed below expectation and the genetically deaf children scored significantly above expectation (Table 2). (Interestingly, using hearing norms, the genetically deaf subjects attained a precisely average group mean of z = -.01, while the NAR subjects produced a mean z score of -1.27, significantly below age expectation). The results differed, however, on the Knox Cubes Test (Arthur, 1947), where the subjects had to recall a temporo-spatial sequence, namely blocks tapped in a specific order. On this task, the genetic subjects continued to out-perform the NAR subjects, and moreover were superior to hearing norms (Table 2). Thus, genetically deaf subjects showed superior skill in immediate recall of spatially presented information, with relatively more difficulty in immediate recall of noncontextual signs or pictures. NAR deaf subjects performed below genetically deaf subjects in all these tests of immediate recall, consistent with the pattern of electrophysiological differences reported above.

General measures of executive control/organization, possibly reflecting frontal lobe functioning, were administered. Superior performance of the genetically deaf subjects over the NAR deaf subjects was again noted on Trail-making (Reitan & Davison, 1974), a task on which subjects must connect a series of numbers (part A) and alternating numbers and letters (part B). Both parts A and B were performed at age expectation by the genetically deaf group but below expectation for the NAR group (Table 2). This result is interesting in that impaired performance on Trail-making is considered to be a good marker of neurological pathology (Reitan, 1971), and in this study subjects with neurologically compromising histories (NAR) were significantly different on this task from subjects without such a history (genetic). Another test purportedly sensitive to attention/executive control is the Stroop Color and Word Test (Golden, 1978). Since deaf subjects' performances were all slower than hearing norms due to signing speed rather than attentional or processing factors, results using hearing norms were not valid (Table 2). The need for deaf norms thus became apparent, and resulted in a separate norming study with deaf adults (Wolff, Radecke, Kammerer & Gardner, 1989, in press).

Several measures of visual processing were included in the battery. Perceptual organization as well as cognitive style were measured with the Rey-Osterrieth Complex Figure (Osterrieth, 1944; Waber & Holmes, 1983), on which subjects must copy and later recall a complex design using a series of different colored pencils in order to monitor process. When scored for organization, both genetic and NAR deaf subjects scored significantly less well than hearing subjects on the copy task, as revealed in Table 2. Moreover, deaf subjects had a greater tendency than hearing subjects to make use of a less differentiated copying style, rather than a clearly part-oriented or configurational style. However, deaf and hearing subjects exhibited equivalent memory for the figure, suggesting accurate encoding (Kammerer, Gardner, & Wolff, 1988).

On the Benton Line Orientation Test (Benton, Varney & Hamsher, 1977), a measure of visual-spatial processing involving appreciation of line angles, a similar pattern was apparent, with both deaf groups performing significantly below hearing norms, but far more so for the NAR deaf than the genetic deaf (Table 2). It had been hypothesized that deaf subjects would out-perform hearing subjects on this task due to the reliance on purely visual processing. The reason for the present results is not apparent. These findings are in contrast to the findings for deaf children on the performance scales of the WISC-R, which show an advantage for the deaf population. It is clear that different visually-based tasks involve varying cognitive demands; for example, many "visual" tasks have a primary linguistic or analytic component suggestive of classical left hemispheric processing demands. Therefore, neural compensation in the visual domain may not be global but rather may relate to certain specific aspects of visual function.

The Developmental Test of Visual-Motor Integration (Beery, 1982) is a structured drawing task where shapes ranging from simple to complex are drawn in separate boxes; the task demands graphomotor precision as well as perceptual analysis. Again, the deaf children scored lower than expectation based on hearing norms, with genetically deaf children scoring higher than the NAR deaf children (Table 2). Further analysis of which components of this task (e.g., graphomotor, or perceptual, or analytic) contributed to these results should be undertaken.

Originally, the Mooney Closure Faces (Mooney, 1957) test was included in our battery

TABLE 3

LATERAL DOMINANCE

	Hearing M (SD)	Genetic Deaf M (SD)	NAR Deaf M (SD)	F (2,164)	p
Hand Total	2.22 (1.78)	1.47 (2.13)	2.00 (1.75)	2.06	NS
Foot Total	1.16 (1.19)	0.43 (1.26)	0.30 (1.16)	9.96	.0005
Eye Total	1.53 (2.01)	1.05 (2.15)	1.33 (2.04)	0.85	NS

to further assess visual integration of complex stimuli. However, attempts to modify the administration of the test negated the validity of the findings, and the measure was therefore dropped. A measure of visual perceptual integration skills, such as the Mooney test or Gordon's visual closure test (Gordon, 1986) would be an important component of a future neuropsychological battery.

Tests of motoric functioning revealed a number of differences between deaf and hearing subjects. Hand dominance was assessed by observing with which hand the subject wrote, reached for an object, and threw a ball. Foot dominance was assessed by observing with which foot the subject kicked a ball and hopped. Eye dominance was assessed by observing with which eye the subject looked through a tube and looked through a pin hole. For each of these tasks a score of 1 was given if the task was performed with the right side, and a score of -1 was given for left side performance. Thus the Handtotal variable ranged from +3 to -3, and Eyetotal and Foottotal ranged from +2 to -2. There was no significant difference among the deaf and hearing groups for hand or eye dominance, although there was a trend for less right handedness and eyedness in genetic and NAR deaf than hearing subjects. However, a highly significant difference was found between deaf and hearing subjects on foot dominance, with both groups of deaf subjects clearly exhibiting a greater tendency toward mixed or left-footedness (Table 3). Because footedness is less subject than handedness to influences of cultural bias and overlearning (e.g. forcing a naturally sinistral child to write with the right hand) foot dominance is thought to be a sensitive and relatively uncontaminated marker for organic insult or atypical cerebral organization (Peters, 1988). Thus, the present finding is consistent with a number of other measures in this study that suggest a pattern of cerebral organization in deaf children differing from the pattern observed among hearing children.

The Timed Motor Examination was administered to assess general motoric functioning, possible asymmetries in performance, and dysrhythmia or overflow suggestive of neurological involvement. Since norms for the Timed Motor Examination extend only up to the age of 11 years (Denckla & Rudel, 1978), deaf-hearing comparisons for this instrument are based on an attenuated sample. Fine motor speed in both right and left hand and foot tasks was either equal to or faster for deaf children than for hearing children in the normative sample (Table 2). This pattern was more pronounced among the genetic group than the NAR deaf group. Similarly, deaf children performed age-appropriately on hearing norms on the Purdue Pegboard Test, another measure of motor speed. The one exception was a slightly below average score for genetically deaf subjects using their preferred hand, but this difference was quite small.

The Meadow-Kendall Social-Emotional Assessment Inventory (Meadow, 1980), which was specifically designed for deaf children, was chosen as a measure of general social-emotional functioning. On this questionnaire, completed by school-based personnel, our subjects for the most part scored within the average range on the three derived factors: Social Adjustment, Self Image, and Emotional Adjustment (Table 4). This suggests that as a group the emotional adjustment of these subjects was typical of the general population of deaf students, for which

TABLE 4

EMOTIONAL/BEHAVIORAL MEASURES
(Conners Teacher Rating Scale results are given in T-scores. Meadow-Kendall SEAI results are given in z-scores.)

VARIABLE	HEREDITARY M (SD)	HEREDITARY p<	AT-RISK M (SD)	AT-RISK p<
CONNERS TEACHER RATING SCALE				
Hyperactivity	53.08 (12.56)	NS	54.81 (10.15)	.01
Conduct Disorder	58.16 (16.73)	.001	56.41 (12.81)	.001
Emotionally Indulgent	56.57 (15.07)	.001	56.41 (14.40)	.001
Anxious/Passive	51.62 (10.82)	NS	55.31 (13.45)	.01
Asocial	52.08 (13.80)	NS	53.07 (11.32)	.05
Daydreaming	52.08 (14.65)	NS	53.36 (12.70)	.05
Standard Hyperactivity Index	58.81 (16.66)	.001	61.60 (19.07)	.001
MEADOW KENDALL SOCIAL-EMOTIONAL ASSESSMENT INVENTORY				
Social Adjustment	.303 (1.26)	NS	- .01 (.93)	NS
Self Image	.159 (.92)	NS	-.12 (1.11)	NS
Emotional Adjustment	.646 (1.24)	.001	.07 (1.10)	NS

this inventory was developed and normed. The one exception to this was the mean score of the genetic group on the Emotional Adjustment factor, suggesting the possibility that these genetically deaf subjects enjoy superior emotional well-being.

Since there at present exists no teacher rating scale designed specifically to assess deaf children for hyperactivity, attentional difficulties, and conduct problems, the Conners Teacher Questionnaire (Conners, 1969; Trites & Blouin, 1982), which is commonly used in clinical practice and research settings, was administered. Both genetic and NAR deaf groups scored significantly above the age referenced norms (which are given in terms of T-scores rather than z-scores, a convention we chose to adopt on this instrument for the sake of consistency with usual practice) on the derived Standard Hyperactivity Index (Table 3), which is described by Conners as a measure of "core psychopathology" (Conners, 1985). Deaf subjects also scored significantly higher than hearing on the Conduct Disorder and Emotionally Indulgent derived factors. The Conduct Disorder factor includes such behaviors as quarrelsomeness, lying and uncooperativeness, while the Emotionally Indulgent factor includes such behaviors as temper outbursts, emotional sensitivity, and over-seriousness. Caution must be used in interpreting these results, since the application of 'hearing' norms to deaf subjects may be inappropriate due to the possible presence of atypical endorsement frequencies for the target group, leading to measurement biases. Nevertheless, since the informants for the Conners instrument were specialists in deaf education, one may assume a certain degree of sensitivity toward the issue of test bias. Differences between NAR and genetically deaf children on this measure give further credence to the results: NAR deaf children, but not genetically deaf children, exceeded hearing norms on factors of Hyperactivity (classic attention deficit disorder symptoms such as fidgeting, restlessness, short attention span), Anxious-Passive (submissive, shy, fearful), and Daydreaming (socially isolated, attendance problem), suggesting the presence of greater psychopathology in NAR than genetic deaf children. This pattern, observed on other measures in this study and elsewhere, could not have resulted from biased norms, since both groups in question consist of deaf children, and any bias would therefore apply equally.

An interesting correlate of these emotional/behavioral results was found in the Language Proficiency Ratings: the tendency for deaf children to be rated in a healthy direction for emotional/behavioral difficulties (relative lack of problems), on both Meadow-Kendall and Conners instruments, was positively correlated with teacher ratings of manual communication skill. One may hypothesize that a common underlying pathology can impair both communication skills and mental health, and/or that the presence of good communication skills facilitates healthy adjustment, and/or that emotional maladjustment predisposes against optimal acquisition of communication skills.

Conclusion

The following conclusions reflect the research results presented above, as well as insights and experience garnered during the process of formulation and administration of these assessment procedures.

Topographic distribution of EEG coherence, phase, and power suggests the existence of deaf-hearing differences in cortical organization, with some regions appearing less neurally differentiated in deaf than in hearing subjects. Greater differentiation, possibly reflecting compensatory processes, appears to be present for certain other cortical areas in the deaf children. Since these differences are based on data obtained while the subjects were in a resting state, the implications for cerebral processing *per se* are not entirely determined. Nevertheless, neuropsychological test data do reflect various deaf-hearing differences, consistent with the view that some aspects of cerebral function are differently organized in deaf individuals.

Although this paper has focused on deaf-hearing differences in cortical functioning, clearly no singular deaf profile is suggested. The pattern of differences noted between deaf and hearing subjects reflects group means, and does not address the considerable individual differences found in the data. These results vary in relation to cause of deafness, with genetically deaf subjects manifesting a number of advantages over subjects whose deafness is attributable to organic insult. Although we know that there are significant pattern differences, there is no ready measure of the importance or relevance of the differences. Differences may be apparent between any two distinct groups: for example, the cognitive profile of musicians is likely to be different from that of accountants (Gardner, 1986). Genetic makeup as well as the linguistic and non-linguistic environment in which a child develops are likely to impact upon the development of cognitive processing.

The pattern of differences between deaf and hearing subjects should also not be seen as a 'deficit' pattern. Clearly the similarity in many test scores in deaf and hearing persons, despite neuropsychological differences, suggests that different strategies for cognitive processing that are used by our groups can be equally effective. In other words, cognitive style, which can be thought of as an aggregate of strategies and meta-strategies, may be different, but many different cognitive styles can subserve adaptive functioning.

Apart from the broad pattern of differences, the specific neuropsychological test data suggest direct implications and cautions for using neuropsychological instruments with deaf children and adults. First, it is apparent that norms derived from the hearing population cannot routinely be applied to the deaf population. Deaf subjects performed above, below, and at the same level as the hearing norms, depending on the the task. Using neuropsychological tests to determine deficit areas of functioning in individual deaf subjects would thus require deaf norms to evaluate the subjects in relation to their deaf peers. In terms of cognitive style, also, differences on neuropsychological tests have been noted between deaf and hearing subjects (Kammerer, Gardner, and Wolff, 1988). Thus, even when performance levels are the same, deaf subjects may solve tasks using a different style or strategy, which has implications for clinical practice.

Clearly, our deaf subjects performed well on some perceptual tasks and had more difficulty on others. Careful analyses of the task demands reveal that multiple systems are involved (e.g. perceptual, linguistic, organizational), which explains why certain non-berbal tasks are more difficult. This suggests that, when attempting to determine which tests are "fair" for deaf subjects in terms of task demands, tasks cannot be labelled simplistically as 'perceptual' or 'language based.' It is apparent that one needs several measures of each basic area of neuropsychological interest, in order to estimate more effectively the subject's underlying functioning, and in order to observe individual ability to manage different demands within tasks.

Caution must also be applied in relating the group differences presented here to an individual's level and style of functioning. Factors to be taken into account include level of deafness, etiology of deafness, and early linguistic environment. In the present study, deaf subjects were divided on the basis of cause of deafness. In general, the NAR group performed less well than the genetic group, but this was not true of all subjects. Although the NAR group was separated from genetic because cause of deafness *may* produce other neurological findings, it should not be presumed that all subjects with these etiologies will show deficits. It should also be noted that some tasks differentiated these groups better than others, suggesting greater sensitivity to the possibility of neurological underpinnings. The best use of the neuropsychological data with deaf individuals ideally should include a careful analysis of individual styles of task solution which should indicate general learning/cognitive processing style, and strengths and weaknesses of functioning; indeed, such an analysis is more relevant for remedial planning than individual scores on given tasks.

A great deal of further research in the fields of neuropsychology and neurophysiology of deafness remains to be done. To develop a better understanding of the present neurophysiological findings, future research should examine EEG or other brain imaging measures (e.g., regional cerebral blood flow) taken during the processing of various tasks differing in cognitive, perceptual and linguistic demands. To utilize neuropsychological measures most effectively in clinical settings, and in order to provide information to aid in remedial planning, more comprehensive deaf norms must be established and the validity of each test instrument must be demonstrated with this population. Only then will a test battery be fully useful in describing healthy adaptations of cognitive style, as well as in detecting specific neurological and cognitive difficulties.

Appendix

EEG Mapping in Relation to Neuropsychological Test Results

A third phase of data analysis has comprised efforts to find statistical relationships between EEG indices and neuropsychological measures. In this Appendix we present, with minimal interpretation, the results of a factor analysis based on a combination of EEG indices and neuropsychological measures.

A set of anatomically aggregated EEG variables were developed to parsimoniously characterize coherence, phase and power findings (e.g., the mean coherence score of all significant derivations in the left fronto-temporal region analysis along with a set of neuropsychological scores selected for maximal contribution of variance on previous analyses. The result was a five factor solution that accounted for 40.6% of the total variance. More interestingly, four of the five factors had significant loadings of *both* EEG variables and neuropsychological measures, and in those instances, we explored correlations between the two classes of variables.

Factor 1, accounting for 11.1% of the variance, loaded most heavily on emotional/behavioral indices computed from the Conners and Meadow-Kendall questionnaires, with weaker loadings of fine motor and visuospatial variables, as well as age. A weak loading was also found for theta left temporo-frontal coherence. Significant positive but weak correlations were found between theta left temporo-frontal coherence and various Conners and Meadow Kendall indices as well as the VMI, Rey-Osterrieth Complex Figure copy score, and age.

Factor 2, accounting for 10.3% of the variance, revealed psychometric loadings that were strongest for measures of intellectual and spatial functioning including the WISC-R subtests, VMI, Benton, Trailmaking, Stroop word condition, and cause of deafness. EEG variables loading heavily on this factor include left and right posterior (occipito-pariental and posterior temporo-parietal) coherence, as well as left temporo-frontal coherence. In general for these variables, negative correlations occurred whereby stronger performance on the relevant neuropsychological measures was related to lower coherence in the regions mentioned.

Factor 3 accounted for 8.5% of the variance, and loaded most heavily on tasks requiring steady output, sustained attention, and organization including the Stroop (word, color, and color-word), age, WISC-R Coding, Rey Auditory-Verbal, Rey-Osterrieth Complex Figure copy, and selected motor indices including the tendency to produce mirror overflow movements (synkinesias) during fine motor activity. This was accompanied by loadings of both right and left alpha and beta phase, alpha, beta and theta right frontal coherence, and alpha left temporo-frontal coherence. The pattern of correlation revealed that better performance on this set of neuropsychological measures was related to lower coherence and phase in the regions and frequencies mentioned. However, age and motor speed were associated with higher coherence and phase. Interestingly, a negative correlation between age and a number of the neuropsychological indices suggests a tendency for these deaf subjects to fall progressively behind age expectation over time.

Factor 4, accounting for 6.0% of the variance, had notable loadings of the Rey Auditory VLT and the production of arm posturing under one of the Stressed Gaits (out). EEG variables with the strongest loadings were those measuring bilateral frontal coherence, followed by right frontal coherence, and right hemispheric phase. Generally, better performance on the Rey Auditory Verbal Learning Test was associated with lower coherence, while the tendency to emit posturing during Stressed Gaits was associated with higher coherence and right theta phase but lower right alpha phase.

Factor 5 accounted for 4.6% of the variance and had only one neuropsychological variable loading: "hand total", a summary score reflecting the degree of right or left hand cominance. Greater right hand dominance was associated with lower frontal total power, often viewed as an index of cortical maturation, as well as with higher right hemispheric coherence, both posterior and anterior, but lower left temporo-frontal alpha coherence. Greater right hand dominance was also associated with higher right occipito-parietal phase.

BRAIN-BEHAVIOR RELATIONS IN DEAF CHILDREN: THE GALLAUDET NEUROBEHAVIOR PROJECT

REFERENCES

Arthur, G. (1947). **A Point Scale of Performance Tests.** Revised Form II. New York: Psychological Corporation.

Beery, K.E. (1982). **Revised Administration, Scoring, and Teaching Manual for the Developmental Test of Visual-Motor Integration.** Cleveland: Modern Curriculum Press.

Brown, S.C. (1986). Etiological Trends, Characteristics, and Distributions. In A.N. Schildroth & M.A. Karchmer (Eds.); **Deaf Children in America** (pp. 33-54). Boston: Little, Brown and Co.

Conners, C.K. (1969). A teacher rating scale for use in drug studies with children. **American Journal of Psychiatry, 126,** 884-888.

Denckla, M.B. & Rudel, R.G. (1978). Anomalies of motor development in hyperactive boys. **Annals of Neurology, 3 (3),** 231-233.

Gardner, H. (1986). **Frames of Mind.** New York: Basic Books.

Globus, A., Rosenzweig, M.R., Bennett, E.L., & Diamond, M.C. (1973). Effects of differential experience on dendritic spine counts in rat cerebral cortex. **Journal of Comparative and Physiological Psychology, 82,** 175-181.

Golden, C.J., (1978). **Stroop Color and Word Test.** Chicago: Stoelting Co.

Gordon, H.W. (1986). The Cognitive Laterality Battery: Tests of specialized cognitive functions. **International Journal of Neuroscience, 29,** 223-244.

Greenough, W.T., Black, J.E., & Wallace, C.S. (1987). Experience and brain development. **Child Development, 58,** 539-559.

Hiskey, M.S. (1941). A new performance test for young deaf children. **Education and Psychological Measurement, 1,** 77-84.

John, E.R., Karmel, B.Z., Corning, W.C., Easton, P., Brown, D., Ahn, H., John, M., Harmony, T., Prichep, L., Toro, A., Gerson, I., Bartlett, F., Thatcher, R., Kaye, H., Valdes, P., & Schwartz, E. (1977), Neurometrics. **Science, 196,** 1393-1410.

Kammerer, B., Gardner, J., and Wolff, A. (1988). Rey-Osterrieth drawings of deaf children with different etiologies of deafness. **Journal of Clinical and Experimental Neuropsychology, 10,** 46.

Martin, D.S. (1985). Introduction. In D.S. Martin (Ed.); **Cognition, Education, and Deafness** (pp. 2-13). Washington, D.C.: Gallaudet College Press.

Matousek, M., & Petersen, I. (1973). Frequency analysis of the EEG in Normal Children and Adolescents. In P. Kellaway & I. Petersen (Eds.), **Automation of Clinical Electroencephalography** (pp. 603). New York: Raven Press.

Meadow, K.P. (1980). **Meadow/Kendall Social-Emotional Assessment Inventory for Deaf Students Manual.** Washington, D.C.: Pre-College Programs, Gallaudet College.

Mooney, C.M. (1957). Age in the development of closure ability in children. **Canadian Journal of Psychology, 11,** 219-226.

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

Nunez, P. (1981). **Electrical Fields of the Brain: The Neurophysics of EEG.** New York: Oxford University Press.

Orr, F.C., DeMatteo, A., Heller, B., Lee, M., & Nguyen, M. (1987). Psychological assessment. In H. Elliott, L. Glass & J.W. Evans (Eds.), **Mental Health Assessment of Deaf Clients: A Practical Manual** (pp. 93-106). Boston: Little, Brown and Co.

Reitan, R.M. & Davison, L.A. (1974). **Clinical Neuropsychology: Current Status and Applications.** New York: Hemisphere.

Reitan, R.M. (1971). Trail making test results for normal and brain-damaged children. **Perceptual and Motor Skills, 33,** 575-581.

Rubel, E.W. (1984). Ontogeny of auditory system function. **Annual Review of Physiology, 46,** 213-229.

Saltzberg, B. (1985). Special electrophysiological tests. In R.C.W. Hall & R.P. Beresford (Eds.); **Handbook of Psychiatric Diagnostic Procedures, Vol. 2,** (pp. 137-150). Jamaica, NY: Spectrum Publications.

Samar, V.J. (1983). Evoked potential and visual half-field evidence for task-dependent cerebral asymmetries in congenitally deaf adults. **Brain and Cognition, 2,** 383-403.

BRAIN-BEHAVIOR RELATIONSHIPS IN DEAF CHILDREN: THE GALLAUDET NEUROBEHAVIORAL PROJECT

REFERENCES

Sisco, F.H. & Anderson, R.J. (1980). Deaf children's performance on the WISC-R relative to hearing status of parents and child-rearing experiences. **American Annals of the Deaf, 125,** 923-930.

Taylor, E.M., **Psychological appraisal of children with cerebral defects.** Cambridge, Mass.: Harvard University Press.

Thatcher, R.W., Walker, R.A., & Giudice, S. (1987). Human cerebral hemispheres develop at different rates and ages. **Science, 236,** 1110-1113.

Thatcher, R.W., Krause, P.J., & Hrybyk, M. (1986). Cortic-cortical associations and EEG coherence: A two-compartmental model. **Electroenceph. Clin. Neurophysiol., 64,** 123-143.

Trites, R.L., Blouin, A.G.A., & Laprade, K. (1982). Factor analysis of the Conners Teacher Rating Scale based on a large normative sample. **Journal of Consulting and Clinical Psychology, 50,** 615-623.

Vernon, M. (1968). Fifty years of research on the intelligence of deaf and hard-of-hearing children; a review of literature and discussion of implications. **Journal of Rehabilitation of the Deaf, 1,** 1-12.

Vernon, M. & Oettinger, P. (1981). Psychological evaluation of the deaf and hard-of-hearing. In L.K. Stein, E.D. Mindel, & T. Jabaley (Eds.). **Deafness and mental health.** New York: Grune and Stratton, 49-64.

Wechsler, D. (1974). **WISC-R Manual. Wechsler Intelligence Scale for Children - Revised.** New York: Psychological Corporation.

Wolff, A.B. & Harkins, J.E. (1986). Multihandicapped students. In A.N. Schildroth & MA. Karchmer (Eds.); **Deaf Children in America** (pp. 55-81). Boston: Little, Brown and Co.

Wolff, A.B. & Thatcher, R.W. (in press). Evidence of cortical reorganization in deaf children. **Journal of Clinical and Experimental Neuropsychology.**

Wolff, A.B., Radecke, D.D., Kammerer, B.L., & Gardner, J.K. (in press). Adaptation of the Stroop color and word test for use with deaf adults. **The Clinical Neuropsychologist.**

Zieziula, F.R. (Ed.) (1982), **Assessment of Hearing-Impaired People.** Washington, D.C.: Gallaudet College Press.