Brain and Language **72,** 238–245 (2000)
doi:10.1006/brln.2000.2287, available online at http://www.idealibrary.com on IDEAL®

Predicting Dyslexia at 8 Years of Age Using Neonatal Brain Responses

Dennis L. Molfese

Department of Psychological and Brain Sciences, University of Louisville, Louisville, Kentucky 40292-0001

Auditory event-related potentials recorded at birth to speech and nonspeech syllables from six scalp electrodes discriminated between newborn infants who 8 years later would be characterized as dyslexic, poor, or normal readers. These findings indicate that reading problems can be identified and possible interventions undertaken up to 9 years earlier than is currently possible. © 2000 Academic Press

Key Words: dyslexia; reading; laterality; auditory evoked response; event-related potential, ERP; electrophysiology.

INTRODUCTION

This work is based on a subset of children tested as part of a larger longitudinal study, which followed 186 full-term children from birth through 8 years of age. Children were tested within 36 h of their birth and then in successive years within 2 weeks of each birthday anniversary. Testing involved the recording of auditory event-related potentials (ERPs) from electrodes placed on the infant and child's scalp at locations over the left and right frontal, temporal, and parietal regions of the brain and referenced to linked ears (Molfese & Molfese, 1985, 1997). ERPs were elicited by repetitions of speech and nonspeech sounds presented in random orderings. A number of IQ and language-related tests were then administered to the children at 8 years of age. The major finding of this study is that amplitude and latency measures of three ERP components recorded at birth discriminated with 81.25% accuracy among three groups of children identified as normal, poor, or dyslexic readers based on reading and IQ scores obtained at 8 years of age.

ERPs recorded to a variety of speech and nonspeech sounds have previously been studied in newborn infants and young children. These studies found that ERPs differ as a function of the evoking sounds and thus reflect acoustic differences (Molfese & Molfese, 1979, 1980, 1985, 1997). Several studies reported that ERPs are sensitive to phonetic differences as well—differences which are important to discriminating between words. Developmentally, the auditory ERPs change as a function of age and appear to reach adult levels by late adolescence.

Support for this work was provided in part by a grant from the National Institutes of Health (R01 HD17860).

Please address correspondence and reprint requests to Dennis L. Molfese, Department of Psychological and Brain Sciences, 317 Life Sciences, University of Louisville, Belknap Campus, Louisville, KY 40292-0001. E-mail: dmolfese@louisville.edu.

0093-934X/00 $35.00

METHODS

Subjects. For this study, data from a total of 48 children composed of 17 dyslexics, 7 poor readers, and 24 controls were analyzed. The dyslexic children were identified at 8 years of age as having normal full scale IQ (FSIQ) scores (mean FSIQ = 110.0) as measured by the Wechler Intelligence Scales for Children-3 (Wechler, 1991, WISC-3), although their reading scores from the Wide Range Achievement Test 3 (Wilkinson, 1993, WRAT) were below average (mean = 80.6). The Poor Readers had both low reading scores (mean WRAT = 85.4) and low WISC Full Scale IQ scores (mean FSIQ = 96.9). Although the FSIQ scores of the Poor Readers and Dyslexics differed from each other, their reading scores did not differ significantly. The Control children were matched to the Full Scale IQ scores of the Dyslexic children (mean WISC FSIQ = 111.7), although their WRAT reading scores were higher than those obtained by both the Poor Readers and Dyslexics (mean WRAT = 103.75). The Poor Readers included 3 males and 4 females, the Dyslexic group included 8 males and 9 females, and the Control group included 11 males and 13 females, to match the sex distribution of the Poor Readers and Dyslexics. The birth characteristics of all 48 full-term infants were unremarkable in that all had Apgar scores in the normal range and none were identified as at-risk at birth. The birth characteristics of the three groups for gestational age and Apgar scores did not differ from each other [Control Group: gestational age = 39.54 (SD = 1.50), Apgar 1 min = 7.75 (SD = 1.57), Apgar 5 min = 8.79 (SD = 1.21); Dyslexic Group: gestational age = 39.94 (SD = 1.43), Apgar 1 min = 7.94 (SD = 0.75), Apgar 5 min = 8.82 (SD = 0.53); Poor Reader Group: gestational age = 39.43 (SD = 1.81), Apgar 1 min = 7.29 (SD = 1.98), Apgar 5 min = 9.00 (SD = 0.58)].

Stimuli. In this experiment, phonetic discrimination abilities were tested in the 48 newborn infants by recording ERPs to repeated series of four sounds that began with an initial consonant transition 50 ms in duration that was followed by a 250-ms steady-state vowel. These sounds were synthetically produced, composed of three formants, and varied in two dimensions (Cutting, 1974). The first dimension involved changes in the second formant transition. An initial upgliding (i.e., rising) second formant transition characterized the consonant sound portion of the /bi/ syllable, while a falling second formant transition characterized the consonant portion of the /gi/ stimulus. The first and third formants of both consonant sounds contained initial up-gliding components for the two syllables. The second feature, formant bandwidth, distinguished the two speech syllables from the two nonspeech sounds. The speech sound versions (normal speech formant) of the /bi/ and /gi/ sounds were composed of three formants with bandwidths of 60, 90, and 120 Hz for formants 1, 2, and 3, respectively. The three formants of the nonspeech versions (sinewave), on the other hand, all had bandwidths of 1 Hz. Rise and decay times were equivalent across sounds. Twenty-five orderings of the four sounds were digitized and presented through a speaker positioned approximately 1 m over the midline of the infant's head. Stimulus presentation was at 80 dB SPL (A) as measured at the infant's ears.

Procedures. The ERP technique involved placing silver–silver chloride electrodes on the scalp of each infant and then recording their brain responses to a random series of speech and nonspeech sounds. Six electrodes were placed over the left and right sides of each infant's head at frontal, temporal, and parietal scalp locations and referred to linked ear references.

These placements included two electrodes placed, respectively, over the left (T3) and right (T4) temporal areas as specified by the Ten-Twenty System (Jasper, 1958); a third electrode was placed at FL, a point midway between the external meatus of the left ear and Fz; a fourth electrode was placed at FR, a position midway between the right external meatus and Fz; a fifth electrode was placed at PL, a point midway between the left external meatus and Pz; and a sixth electrode was placed at PR, a point on the right side of the head midway between the right ear's external meatus and Pz. Thus, these electrode placements were over the left frontal (FL), temporal (T3), and parietal (PL) areas of the brain and the corresponding areas of the right hemisphere (FR, T4, and PR, respectively). These placements were used to assess left versus right hemisphere responses and responses within each hemisphere concerning general language perception areas commonly thought to be localized to the left temporal and parietal language receptive regions of the brain as well as the language production areas of the frontal lobe. The electrical activities recorded from these scalp electrode positions were referred to electrodes placed on each earlobe and linked together (A1, A2). Additional electrodes at a canthal position and at a supraorbital site relative to the right eye were used to monitor eye artifacts. Electrode impedances were under 5 kohm and did not vary more than 1 kohm between electrode sites on the scalp or the two ear reference electrodes, as indicated by measurements before and after the test session.

Each infant was tested while in a bed that was reclined at a 40° angle throughout the test session. Once all electrodes were in place and the impedances measured, the stimuli were presented while the infant was in a quiet awake state. Continuous monitoring of the infant's ongoing electroencephalographic (EEG) and electromyographic (EMG) activity, as well as behavioral observation, was used to monitor state and determine when stimulus presentation should occur. During periods of motor activity or sleep, stimulus presentation was suspended. Testing was then resumed when the infant's alertness and motor activity returned to an acceptable level.

The ongoing EEG during the test session was amplified 80,000 times using modified Tektronix differential amplifiers with the bandpass flat between 0.1 and 30 Hz. These amplified signals were then recorded onto cassette tape using a Vetter C-8 FM tape recorder. The analogue FM tapes were then played back offline and the auditory ERP portions of the EEG signal digitized using a Macintosh Plus microcomputer and the EPACS software package (Molfese, 1988). On each trial an ERP was digitized separately for each electrode site, stimulus event, and infant. Each ERP consisted of 70 data points, sampled at 10-ms intervals and collected sequentially over a 700-ms period beginning at stimulus onset. These digitized values were then stored and subsequent analyses performed offline following completion of the testing session.

RESULTS

Artifact rejection was carried out on the ERP data for each electrode to eliminate the ERPs contaminated by motor movements from further analysis. If an artifact (operationally defined as a shift in the voltage level in excess of ±40 μV) occurred on any one electrode channel during the 65-ms pre- or 700-ms poststimulus period on any trial, all of the ERPs collected across all of the electrode sites for that trial were discarded from subsequent analyses. This procedure, which was based on the peak-to-peak amplitudes, resulted in rejecting fewer than 15% of the trials for each infant. Rejection rates were comparable across the four sounds. Following artifact rejection, the single trial data were then averaged separately for each electrode site and sound. Thus, 24 averages were obtained for each infant and then analyzed using standard peak amplitude and latency measurements.

Baseline-to-peak amplitude (calculated from the average prestimulus period to a peak within the brainwave) and peak latency measures (calculated from stimulus onset to the maximum point of a peak within the brainwave) were calculated for three component peaks of each neonatal ERP. These peak measures then served as dependent measures in a discriminant function analysis to classify children's reading performance at 8 years of age based on previous work predicting later developmental outcomes (Molfese & Molfese, 1985, 1997). This included (a) the initial negative–positive shift in the ERP in the region from the first large negative peak (N1, mean peak latency = 174.3 ms, $SD = 31.2$, mean baseline-to-peak amplitude = −2.4 μV, $SD = 1.2$ μV) to the following positive peak (P2, mean peak latency = 308.7 ms, $SD = 38.2$, mean peak amplitude = 3.3 μV, $SD = 1.2$ μV) and (b) a second large negative peak (N2, mean peak latency = 458.0 ms, $SD = 32.8$, mean peak amplitude = −3.5 μV, $SD = 1.2$ μV).

The discriminant function used six neonatal ERP responses to discriminate among the Control, Dyslexic, and Poor Reader groups at eight years of age. These variables included three peak latency measures recorded over the left and right hemispheres and three baseline-to-peak amplitude measures recorded over the right hemisphere. The three peak latency measures included the first large negative peak latency (N1) to the speech syllable, /gi/, recorded at both the left hemisphere frontal and parietal electrode sites, as well as at the right temporal hemisphere. The three amplitude measures included (1) the second large negative peak (N2) that differed between groups in response to the /gi/ speech syllable at the right hemisphere frontal electrode site; (2) the N1 amplitude change recorded at the right temporal hemisphere electrode site elicited in response to the /bi/ nonspeech syllable; and (3) the second large positive peak amplitude (P2) elicited in response to the /bi/ speech syllable. These six measures resulted in the identification of two significant canonical discriminant functions, $\chi^2 = 55.6$, $df = 10$, $p < .00001$, Wilks' $\lambda = .27014$, and $\chi^2 = 16.9$, $df = 5$, $p < .0058$, Wilks' $\lambda = .68003$, which, as indicated in Table 1, correctly classified 81.25% of the entire sample (39 of 48 children) at 8 years of age. Using the neonatal ERP measures, 7 of 7 Poor Readers were correctly classified (100%), 13 of 17 Dyslexic children were correctly classified (76.5%), and 19 of 24 of Control children (79.2%). These classifications are well above chance levels. The chance classification rate for classifying each of the three groups accurately was calculated using the proportional change criterion. In this case the formula is $(\text{proportion in group } 1)^2 + (\text{proportion in group } 2)^2 + (\text{proportion in group } 3)^2$. This led to a chance classification of .396, [i.e., $(.146)^2 + (.354)^2 + (.50)^2 = .396$]. Two times chance classification is .792, the level at which the control group was correctly classified. Given that overall chance classification is .396, the present accuracy in predicting from birth measures to 8 years of age is at least two times greater than chance. If reading interventions were attempted shortly after birth on the basis of these data, 22 of 24 children in need of

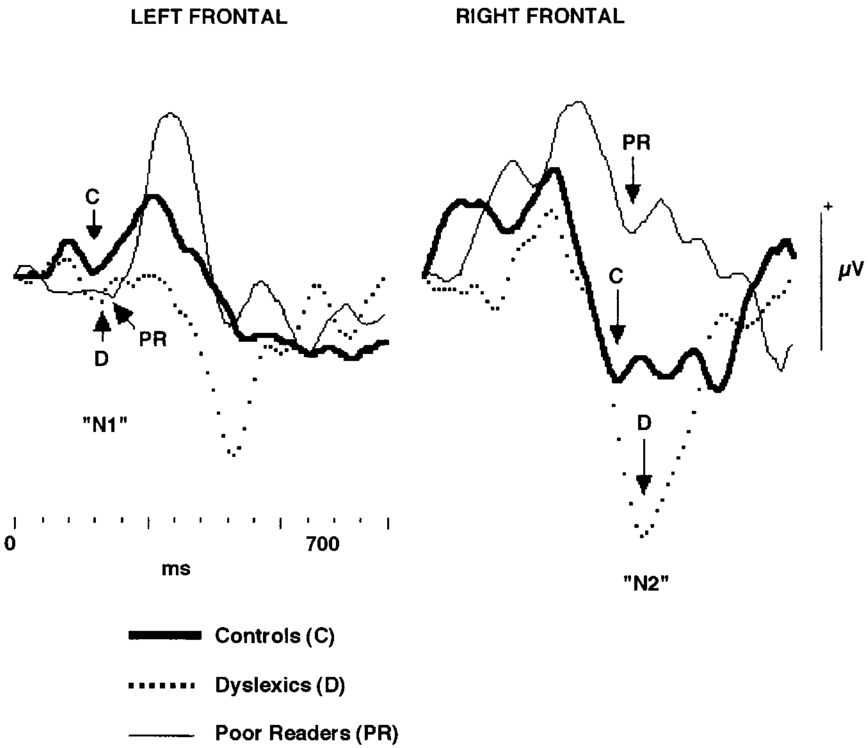

FIG. 1. The ERPs recorded over the left and right hemisphere frontal regions from the three groups of infants at birth in response to the speech syllable /bi/. The dark solid line characterizes the Control group (C), the dashed line indicates the Dyslexic group (D), and the thin, solid line the Poor Reader (PR). The left hemisphere N1 latency is shortest for the Controls and longest for the Poor Readers. The N1 is not well defined in either the Dyslexics or the Poor Readers. Right hemisphere N2 peak amplitudes are largest for the Dyslexics and smallest for the Poor Readers. The calibration marker is 2 μV, with positive up. Wave form duration is 700 ms.

intervention at 8 years of age could have been targeted to receive intervention beginning at birth, while only 5 of 24 children who did not require intervention would have received it. Thus, ERP measures shortly after birth demonstrate high accuracy (identifying nearly 92% of children in need of intervention by 8 years) and generate relatively few false positives in predicting reading problems 8 years later.

DISCUSSION

Whatever the bases for such differences, these results strongly indicate that auditory ERPs recorded within 36 h of birth successfully discriminate at well above chance levels the reading performance of these same children 8 years later. These findings build upon previously reported studies (Molfese & Molfese, 1985, 1997) and demonstrate that very high predictive accuracy can extend through 8 years of age. The obvious question that arises from these results concerns how any measure, behavioral or brain, can discriminate later developmental outcomes over a large age range with such high accuracy. Are human accomplishments predetermined from birth? Are genetic factors so potent that they all but force certain developmental outcomes despite the influence of environmental factors? Molfese and Molfese (1997) hypothesize that these data reflect the state of an underlying perceptual mechanism upon which some aspects of later developing and emerging verbal and cognitive processes are based. The marked latency shift in the N1 component that discriminates among the three groups supports this interpretation. Infants whose brains can detect, react to, and process information more quickly will later be advantaged during language development.

As a result of genetic and intrauterine factors, the developing organism develops a set of perceptual abilities responsive to variations in its environment. For most of us, these perceptual abilities are similar and readily enable us to discriminate elements within our environment in quite similar ways. For others, however, aspects of these perceptual skills may not respond to environmental elements in the same manner, resulting in delays or the faulty processing of information. It is these fundamental differences in perceptual skills that set the stage for the results of the present study and the early detection of responses that predict later reading performance. A number of other investigators have recently reported results that could suggest a similar process (Kraus, McGee, Carrell, Zecker, Nicol, & Koch, 1996; Merzenich, Jenkins, Johnston, Schreiner, Miller, & Tallal, 1996; Tallal, Miller, Bedi, Byma, Wang, Nagarajan, Schreiner, Jenkins, & Merzenich, 1996).

TABLE 1

Classification Accuracy Based on Using Neonatal Baseline and Latency Measures to Discriminate between WISC- and WRAT-III Scores for the Control, Dyslexic, and Poor Reader Groups at 8 Years of Age

	Classification results			
		Predicted group membership		
Actual group	No. of cases	3	2	1
Group 1	24	3	2	19
(Controls)		12.5%	8.3%	79.2%
Group 2	17	2	13	2
(Dyslexics)		11.8%	76.5%	11.8%
Group 3	7	7	0	0
(Poor Readers)		100%	0%	0%

Note. Group 1 is the Control group, Group 2 is the Dyslexic group, and Group 3 is the Poor Reader group. Both the number of children classified to each group and the percentage of assignment are included. The percentage of cases correctly classified was 81.25%.

Although the general belief has long existed that language skills are controlled by mechanisms largely restricted to the left hemisphere (Bryden, 1981; Lenneberg, 1967), variables identified in the present study indicate that ERP activity recorded over both the left and right hemispheres successfully discriminated between populations of children with different levels of verbal performance. These findings support a position counter to that of Lenneberg, suggesting that in the early stages of postnatal life, it is the functioning of mechanisms within both hemispheres of the brain that are important to later language development. Such bilaterally represented mechanisms may play a fundamental and crucial role in the later development of verbal abilities.

The finding that electrophysiological measures obtained at birth successfully discriminate between infants who, 8 years later, will display different levels of reading skills raises exciting possibilities regarding the early identification of children with potential language problems. This opens up the possibility that successful intervention of reading and language problems could be carried out *before* these problems later emerge in the child's behavior during the elementary school years. At present, the identification of such reading problems occurs relatively late, often in the third or fourth grade (i.e., 9 to 10 years of age), after it is established that the child is performing substantially below their expected grade level. One consequence of this delayed identification strategy is that it occurs so late in the child's overall cognitive and linguistic development that it may already be pushing the edge of the child's cognitive flexibility and its ability to master new skills. Witelson and Swallow (1987) noted that 10 years of age could mark a major "breaking point" in development since there are marked changes in abilities such as spatial pattern recognition, Braille, and map reading after this time. Others (Curtis, 1977) note that the onset of puberty appears to set limits on the acquisition of certain language and cognitive skills. Thus, interventions begun at approximately 10 years of age could face ceiling limits placed upon their success by the child's developmental level and age. If, however, potential problems in language or cognitive development could be identified much earlier in time, even at birth, planned interventions could be introduced earlier to the child and, consequently, could potentially be more successful in remediating the child's later emerging language problems. Perhaps science is moving closer to the point where we will eliminate learning disabilities, instead of simply attempting to lessen their impact through the training of compensatory skills and strategies.

REFERENCES

Bryden, M. P. 1981. *Laterality.* New York: Academic Press.

Curtis, S. 1977. *Genie: A psycholinguistic study of a modern day "wild child."* New York: Academic Press.

Cutting, J. E. 1974. Two left-hemisphere mechanisms in speech perception. *Perception & Psychophysics,* **16,** 601–612.

Discriminant Function 1995. *SPSS 6.1.1. for the Macintosh.* Chicago: SPSS.

Jasper, H. H. 1958. The ten-twenty electrode system of the International Federation of Societies for Electroencephalography: Appendix to report of the committee on methods of clinical examination in electroencephalography. *Journal of Electroencephalography and Clinical Neurophysiology,* **10,** 371–375.

Kraus, N., McGee, T. J., Carrell, T. D., Zecker, S. G., Nicol, T. G., & Koch, D. B. 1996. Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science,* **273,** 971–973.

Lenneberg, E. 1967. *Biological foundations of language.* New York: Wiley.

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. 1996. Temporal processing deficits of language-learning impaired children ameliorated by training. *Science,* **271,** 77–81.

Molfese, D. L. 1988. *Evoked potential analysis and collection system. (EPACS).* U.S.A. copyright.

Molfese, D. L., & Molfese, V. 1997. Discrimination of language skills at five years of age using event related potentials recorded at birth. *Developmental Neuropsychology, 13,* 135–156.

Molfese, D. L., & Molfese, V. J. 1980. Cortical responses of preterm infants to phonetic and nonphonetic speech stimuli. *Developmental Psychology, 16,* 574–581.

Molfese, D. L., & Molfese, V. J. 1979. Hemisphere and stimulus differences as reflected in the cortical responses of newborn infants to speech stimuli. *Developmental Psychology,* **15,** 505–511.

Molfese, D. L., & Molfese, V. J. 1985. Electrophysiological indices of auditory discrimination in newborn infants: The basis for predicting later language performance? *Infant Behavior and Development, 8,* 197–211.

Molfese, D. L., & Segalowitz, S. 1988. *Brain lateralization in children: Developmental implications.* New York: Guilford.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., Schreiner, C., Jenkins, W. M., & Merzenich, M. M. 1996. Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science, 271,* 81–84.

Wechler, D. 1991. *Weschler Intelligence Scales for Children.* New York: The Psychological Corporation.

Wilkinson, G. S. 1993. *Wide Range Achievement Test.* Wilmington: Wide Range.

Witelson, S., & Swallow, J. A. 1987. Neuropsychological study of the development of spatial cognition. In J. Stiles-Davis, M. Kritchevsky, & U. Bellugi (Eds.), *Spatial cognition: Brain bases and development.* Hillsdale, NJ: Erlbaum. Pp. 373–409.