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Dennis L. Molfese & Victoria J. Molfese

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Discrimination of Language Skills at Five Years of Age Using Event-Related Potentials Recorded at Birth

Dennis L. Molfese and Victoria J. Molfese
Department of Psychology
Southern Illinois University at Carbondale

Limited success has been noted in prior attempts to predict language and cognitive performance during the toddler and preschool years from measures obtained at birth. Most perinatal measures, although demonstrating some success in predicting motor and early cognitive skills at 1 year of age, have generally failed to maintain their predictive effectiveness when used to predict abilities that emerge later in development. However, 1 electrophysiological technique that involves the recording of event-related potentials (ERPs) to speech sounds may provide a means to improve such predictions. This article describes a successful extension of an earlier attempt to predict language performance during the preschool years from neonatal scalp recorded ERPs. Auditory ERPs were recorded from the frontal, temporal, and parietal scalp regions of 71 newborn infants in response to a series of 9 consonant–vowel syllables. Following artifact rejection and averaging, these ERPs were input to a principal components analysis that isolated 7 factors to account for 89.02% of the total variance in the data set. Selected factor scores from 2 factors matching the latency configuration of those identified earlier by D. L. Molfese and V. J. Molfese (1985) were then used in a series of discriminant function analyses to separate these infants into 2 groups based on performance on the verbal subtest of the Stanford–Binet at 5 years of age. Three different discriminant function analyses involving different variables showed high classification accuracy in predicting later developmental outcomes.

Requests for reprints should be sent to Dennis L. Molfese, Department of Psychology, Southern Illinois University at Carbondale, Carbondale, Illinois 62901.

For decades researchers and practitioners have been interested in developing assessment tools for neonates that can be used to predict cognitive development in later infancy and early childhood. Motivating this research has been the belief that early identification of developmental delays and disabilities can lead to earlier and, presumably, more effective intervention. The ideal measures would permit the assessment of abilities at birth, when virtually total populations of infants are readily accessible in hospitals. These ideal measures would be easily administered, cost-effective, and accurate in identifying those infants who are at risk for developmental delays. However, the ideal measures that satisfy all of these criteria have been difficult to identify. The most typical approaches to assessment have involved the use of a wide variety of newborn and early infant measures as predictors and a variety of performance measures obtained later in infancy or childhood as the criterion scores. The newborn and early infancy measures used as predictors have included measures of perinatal complications, neurological and behavioral assessments, electrophysiological measures of brain functioning, and measures reflecting attention and tactile abilities. Criterion measures (scores that are predicted) have included scores on scales such as the Bayley Scales of Infant Development (Bayley, 1969), the Denver Developmental Screening Test (Dunn, 1965), the Stanford–Binet Intelligence Scale (Thorndike, Hagen, & Sattler, 1986), and the McCarthy Scales of Children's Abilities (McCarthy, 1972).

Many attempts have been made to develop systems in which perinatal risk scores reflecting prenatal, intrapartum, and neonatal complications can be used to predict cognitive functioning in infancy and early childhood. Several researchers have shown that perinatal risk scores are predictive of performance scores on developmental tests within the infancy period (Low et al., 1985; V. Molfese & Thomson, 1985). However, attempts to extend the period to include early childhood have not been as successful. Researchers report that perinatal risk scores were either not predictive of outcomes in preschool and school-age children (e.g., Cohen & Parmelee, 1983; Cristafi, Driscoll, Rey, & Adler, 1987) or the scores were found to be only weak correlates (e.g., Bee et al., 1982; Largo et al., 1989; Silva, McGee, & Williams, 1984). More successful results have been reported when measures obtained in later infancy and early childhood were used to predict later language and cognitive skills (V. Molfese & DiLalla, 1995; V. Molfese, DiLalla, & Lovelace, 1996; Siegel, 1982a, 1982b, 1985; Smith, Flick, Ferris, & Sellman, 1972).

In the majority of published reports, the amount of variance accounted for by the predictor variables, alone or in combination, is low, as is classification accuracy. Nevertheless, recently there have been encouraging signs that long-term predictive accuracy is improving. There has been an increase over the past 5 years in the variance accounted for and an increase in the number of studies reporting predictive relations between neonatal measures and scores in later childhood. Still, the amount of variance accounted for remains less than 60% even over a relatively short time period. Thus, it appears that the dependent variables studied thus far still do not accurately predict later abilities in reliable and meaningful ways.

One procedure that has proven useful in predictive studies of language skills involves the use of scalp electrodes to record auditory event-related potentials (ERP). The ERP is a synchronized portion of the ongoing electroencephalograph (EEG) pattern that is time-locked to the onset of some event in the participant's environment. ERPs are usually represented as complex waveforms that reflect changes in the amplitude and frequency of electrical activity over time. These waveforms are thought to reflect changes in brain activity via fluctuations in the amplitude or height of the wave at different points during the time course of the wave (Callaway, Tueting, & Koslow, 1978). Because of this time-locked feature, the ERP has been shown to reflect both general and specific aspects of the evoking stimulus (D. L. Molfese, 1978a, 1978b) and the individual's perceptions and decisions regarding the stimulus (D. L. Molfese, 1983; Nelson & Salapatek 1986; Ruchkin, Sutton, Munson, Silver, & Macar, 1981).

The ERP technique appears to be particularly well-suited for the neuropsychological study of the infant's language skills, given previous successes in investigations of infant speech perception (D. L. Molfese, 1972; D. L. Molfese, Freeman, & Palermo, 1975; D. L. Molfese & V. J. Molfese, 1979, 1980, 1985; see D. L. Molfese & Betz, 1988, for a review of this literature). Indeed, a series of recent studies demonstrated that ERPs recorded from infants aged 12–16 months can discriminate familiar versus nonfamiliar consonant–vowel (CV) speech syllables (D. L. Molfese, 1989), words from nonwords (D. L. Molfese, 1989, 1990), and learned labels to objects when they are used to appropriately versus inappropriately label those objects (D. L. Molfese, Morse, & Peters, 1990). Such discriminations have also been noted to occur in retarded children (D. L. Molfese, Morris, & Romski, 1990). In adult populations, ERPs have been known to detect linguistic differences such as the emotional quality or connotative meanings of words (Begleiter & Platz, 1969; Chapman, McCrary, Bragdon, & Chapman, 1979) and even differences in the syntactic class of words (Brown, Marsh, & Smith, 1979; D. L. Molfese, Burger-Judisch, Gill, Golinkoff, & Hirsch-Pasek, 1996).

This study is an extension of the work conducted as part of an earlier longitudinal study by D. L. Molfese and V. J. Molfese (1985) that used neonatal ERPs to predict later language and cognitive performance. In the earlier longitudinal study, D. L. Molfese and V. J. Molfese recorded ERPs from scalp electrodes placed over the left and right temporal regions of 16 newborn infants to a series of CV speech syllables and then recorded ERPs again at 6-month intervals through 3 years of age. The averaged ERPs were averaged and then submitted to a principal components factor analysis with varimax rotation. Seven factors (accounting for 79.9% of the total variance) were derived from the analysis on the newborn ERP data. At 3 years of age, the verbal subtest of the McCarthy Scales of Children's Abilities was administered to these children. The average McCarthy verbal score for these 16 children was 50.8 (*SD* = 33.7). The group was then subdivided into two distinct groups: One group was composed of children whose verbal scores were above 50 (mean score = 77.25, *SD* = 15.5), and the second group had verbal scores below 50 (mean score = 20.5, *SD* = 12.6). Although the groups differed markedly in terms of their language scores, they did not differ on other factors such as birthweight, gestational age, Obstetrical Complication Scale scores (Littman & Parmelee, 1978), Brazelton Neonatal Assessment Scale scores (Brazelton, 1973), Bayley Mental scores at 6 and 12 months of age, or socioeconomic measures such as family income, parental education or occupation.

The results showed that three components or waveform peaks of the newborn ERP reflected differential sensitivity to specific consonant and CV characteristics of the evoking stimulus. Intriguingly, although the belief has persisted that only left hemisphere functioning is related to language skills, D. L. Molfese and V. J. Molfese noted that both lateralized and bilateral responses recorded over the temporal regions discriminated between these speech sounds. Furthermore, these lateralized and bilateral ERP components discriminated between children who would go on to develop different levels of language skills 3 years later. Thus, it appeared that there was a definite relation between brain responses recorded shortly after birth and relatively small differences in language performance 3 years later in children who were functioning across a broad range of language development.

This early study showed that ERP techniques hold great potential for early detection of differences in brain functioning that are related to subsequent performance on tests of cognitive and language abilities. To expand the subject sample as well as the predictor and criterion measures, a second longitudinal study was begun in 1986. This new study was designed to study language and cognitive development in a sample of children with normal status. These children were monitored yearly beginning at birth with electrophysiological recording techniques to record their ERPs to CV speech sounds and with standardized tests that provided information on intellectual and cognitive status. This report focuses on the effectiveness of newborn ERPs to classify the performance of 5-year-old children on the verbal subscale of the Stanford–Binet Intelligence Test. The motivation, then, for this study was to, first, verify the results of the earlier work by D. L. Molfese and V. J. Molfese (1985) with a different set of language performance measures and, second, to determine whether the predictions to these measures remained accurate across a longer time span, to 5 years of age.

METHODS

Participants

The 71 Caucasian children (39 female and 32 male) included in this study comprise a subset of the approximately 186 infants who were involved in the longitudinal study when it began in 1986. All infants were tested within 36 hr of birth and again within 2 weeks of their birthdays. These participants were selected from the larger database solely because they had complete data on all variables under study. The specific birth characteristics of this group overall included an average birth weight of 3,465.97 g (*SD* = 725.2), a mean gestational age of 39.5 (*SD* = 2.18), and Agar Scores (Apgar, 1953, 1962) at 1 min of 7.76 (*SD* = 1.4) and at 5 min of 8.9 (*SD* = .9). All infants were tested on the Stanford–Binet Intelligence Scale (Thorndike et al., 1986). The mean verbal IQ of this sample, as measured by the Stanford–Binet Intelligence Test, was 108.03 (*SD* = 8.16, range = 80–129).

Stimuli

Nine synthetically produced CV syllables were used in the study. These five-formant synthetic CV syllables were obtained from S. Blumstein and have been previously investigated in both behavioral (Blumstein & Stevens, 1979) as well as electrophysiological studies (D. L. Molfese, 1980; D. L. Molfese & V. J. Molfese, 1979; D. L. Molfese & Schmidt, 1983). The tokens selected for this study were previously identified by adult participants (Blumstein & Stevens, 1979; D. L. Molfese, 1980) as members of their respective categories. These were Stimulus Tokens 1, 7, and 14 from the /ba, da, ga/ continuum and Tokens 1, 7, and 13 from both the /bi, di, gi/ continuum and the /bu, du, gu/ continuum, respectively. As indicated by Blumstein and Stevens, these stimuli were originally synthesized on a Klatt cascade synthesizer so that the amplitudes of the individual formants were modulated as a function of the respective formant frequencies as in natural speech. To further improve the naturalness of the tokens, the vowels /i/ and /u/ were slightly diphthongized. The central frequencies of the steady-state portion of the formants were constant across the different consonant sounds and only varied as a function of the vowels. Duration of the F1 formant transition varied between 15 and 45 ms across the different tokens as a function of the initial consonant sound as well as the following vowel. Transition duration for all other formants was fixed at 40 ms. Voicing duration was 250 ms. Starting frequencies of F2, F3, and F4 were varied systematically across stimuli. Consequently, although starting frequencies for any individual consonant sound varied as a function of the following vowel, the gross shape of the frequency spectrum during the first 25 ms following consonant release remained relatively constant across different vowel contexts. Two of the CV syllables, /bi, gi/ were similar to two of the syllables that D. L. Molfese and V. J. Molfese (1985) found to successfully discriminate low from high language performers, although they did differ in the number of formants employed. All of the CV syllables were 300 ms in duration, with rise–decay times equated across stimuli. Peak stimulus intensities were also matched. The nine different CVs were arranged on the tape in a block random order, with 20 occurrences of each. The interstimulus interval varied randomly between 3.5 and 6.0 sec in order to reduce habituation and expectancy effects. A square wave pulse was recorded onto the second channel of the stereo tape and occurred 65 ms before the stimulus on the first channel. This pulse served as a trigger for the collection of the ERPs elicited in response to each stimulus event.

Procedures

Electrophysiological measures. Participants were first tested within 36 hr of birth using the following procedure. The head of each infant was measured to identify where electrodes were to be placed. A mark was placed on the scalp immediately anterior to each measured position using a water soluble marker pen. Next, each area was rubbed with a pumice solution to lower skin resistance. The area was then cleaned to remove the residual pumice. A conductive gel, Grass electrode paste (EC–2), was then rubbed into the scalp at this location. This paste was also placed in the cup of each electrode, which was then placed on the scalp. The conductive paste was also placed on a folded 2 cm square of gauze, which was folded and then placed over the back of the electrode. A 1 in. strip of surgical tape was then placed over the back of the electrode and gauze as a further means of holding the electrode to the scalp. Using this procedure, six silver cup scalp electrodes were placed over the left and right sides of each infant's head. These placements included two electrodes placed respectively over the left (T3) and right (T4) temporal areas of the Ten–Twenty System (Jasper, 1958); a third electrode placed at FL, a point midway between the external meatus of the left ear and Fz; a fourth electrode placed at FR, a position midway between the right external meatus and Fz; a fifth electrode placed at PL, a point midway between the left external meatus and Pz; and a sixth electrode placed at PR, a point on the right side of the head midway between the right ear's external meatus and Pz. These electrode placements were over the FL, T3, and PL areas of the brain and the corresponding areas of the right hemisphere (FR, T4, and PR, respectively). These placements were used to reflect left versus right hemisphere responses, and, in addition, 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 activity recorded from these scalp electrode positions was referred to electrodes placed on each earlobe and linked together (A1, A2). 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 CV stimuli were 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 and occurred while the infant was in a quiet awake state. Continuous monitoring of the infant's ongoing EEG and EMG, as well as behavioral observation, were used to monitor state and determine when stimulus presentation should occur. During periods of motor activity or sleep, stimulus presentation was suspended. Testing was 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 band pass flat between .1 and 30 Hz. These amplified signals were then recorded onto cassette tape using a Vetter C–8 FM tape recorder. The analogue tapes were then played back off line and the ERP portions of the EEG signal digitized using a Macintosh Plus microcomputer and the EPACS© software package (D. L. Molfese, 1988).

Language measures. Testing at 5 years of age occurred when the parents brought their child to the university laboratory for the child's annual test session. The children were tested on the Stanford–Binet, including all subtests appropriate for their age and ability levels. The Stanford–Binet is standardized for use with individuals aged 2 through 23 years. The scale scores can be used to obtain a composite IQ score, as well as subscale scores for Verbal Reasoning, Abstract/Visual Reasoning, Quantitative Reasoning, and Short-Term Memory. Administration of the test was done by trained graduate students according to standard procedures. Only the Verbal Reasoning subscale scores were used in the analyses reported here.

Based upon their 5 year performance on the verbal portion of the Stanford–Binet, the 71 participants were divided into two groups—a group of 62 children with verbal IQ scores above 100 (high group) and a second group of 9 children (5 female, 4 male) with scores below 100 (low group). The birth characteristics of the high group included an average birth weight of 3,479.42 g (SD = 725.7), a mean gestational age of 39.55 (SD = 2.24), and Apgar Scores at 1 min of 7.74 (SD = 1.5) and at 5 min of 8.9 (*SD* = .9). The low group was characterized by an average birth weight of 3,373.33 g (*SD* = 758.5), a mean gestational age of 39.3 (*SD* = 1.8), and Apgar Scores at 1 min of 7.89 (*SD* = .93) and at 5 min of 8.78 (*SD* = .44). There were no differences between the two groups for birth characteristics as indicated by *t* tests, $p > .05$. These two groups were then used in the discriminant function procedures described later.

Analyses

To facilitate comparisons with the work of D. L. Molfese and V. J. Molfese (1985) the data reduction and initial analysis procedures employed in the earlier study were also employed with this data set. First, individual ERPs were recorded to each of the auditory stimulus events. Each ERP consisted of 70 data points collected sequentially over a 700 ms period beginning at stimulus onset. On each trial an ERP was digitized separately for each electrode site, stimulus event, and infant. These digitized values were then stored and subsequent analyses were performed off line following completion of the testing session. Artifact rejection was carried out on the ERP data for each electrode to eliminate the ERPs contaminated by motor movements from further analyses. If an artifact (operationally defined as a shift in the voltage level in excess of +/–40 mV) occurred on any one electrode channel during the 65 ms pre- or 700 ms poststimulus period, 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 of single trial responses, resulted in rejecting less than 10% of the trials for each infant. Rejection rates were comparable across the nine stimulus conditions. Following artifact rejection, the single trial data were then averaged separately for each electrode site and stimulus condition. Thus, for each infant, 54 averages were obtained. In this manner, 3,834 averaged ERPs were obtained from the 71 infants in response to nine CV syllables, which were composed of three consonants (*b, d, g*) and three vowels (*a, i, u*) from three electrode sites (frontal, temporal, and parietal) for each of the two hemispheres (left and right).

To further facilitate comparisons with the earlier study, the average ERPs obtained in this study were first submitted to a Principal Components Analysis (PCA) identical to that employed by D. L. Molfese and V. J. Molfese (1985). This procedure has also been used successfully in previous studies. Although there are a variety of different analysis procedures which could be used to analyze the ERP data, this multivariate approach has produced consistent results in programmatic research across a number of laboratories (Brown et al., 1979; Chapman et al., 1979; Donchin, Teuting, Ritter, Kutas, & Heffley, 1975; Gelfer, 1987; D. L. Molfese, 1978a, 1978b; D. L. Molfese & V. J. Molfese, 1979, 1980, 1985; Ruchkin et al., 1981; Segalowitz & Cohen, 1989). For example, D. L. Molfese, in a series of papers investigating speech perception cues such as Voice Onset Time (VOT) and Place of Articulation, has noted consistent systematic effects across studies for each cue (D. L. Molfese, 1978a, 1978b, 1980, 1984; D. L. Molfese & Schmidt, 1983). Moreover, these effects have also been independently replicated using comparable analysis procedures (Gelfer, 1987; Segalowitz & Cohen, 1989). The rationale for the use of this procedure is that it has proven successful both in identifying regions of the ERP where most of the variability occurred across ERPs and subjects, and subsequently in determining if the variability characterized by the different factors was due to systematic changes in the independent variables under investigation.

The PCA procedure behaves somewhat similarly to a factor analysis with the exception that it constructs the factors on the basis of variances instead of correlations (Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982, p. 63). The PCA procedure itself is blind to individual experimental conditions and generates the same solution regardless of the order in which the ERPs are entered. Once the PCA identifies where within the ERPs most of the variability occurred, a discriminant function procedure used the factor scores generated by the PCA to classify the infants into one of two outcome groups at 5 years of age based on the verbal performance subtest of the Stanford–Binet. This procedure directly addresses the question of whether the newborn ERP wave shapes recorded from different electrode sites over each hemisphere in the region characterized by any one factor could be used to correctly classify these children in terms of their language performance 5 years later.

RESULTS

The 3,834 averaged auditory evoked responses each consisted of 70 data points. These formed the input matrix for the PCA using the BMDP4M program from the BMDP87 package (Dixon, 1987). This program first transformed the data into a covariance matrix and then applied the PCA to this matrix. Seven factors accounting for 88.8% of the total variance were selected for further analyses based on the Cattell Scree Test (Cattell, 1966). These factors were then rotated using the normalized varimax criterion (Kaiser, 1958), which preserved the orthogonality among the factors while improving their distinctiveness. This analysis generated factor scores or weights for each of the 3,834 averaged ERPs for each of the seven rotated factors. The 89.02% of the variance isolated by the PCA was characterized by the seven factors (factor loadings). The peak for each factor and the area immediately surrounding it in time indicates that this region of the brain wave changed in amplitude or slope across some proportion of the ERPs in this data.

The centroid or group-averaged ERP for the entire data set and the seven factors isolated by the PCA procedure are presented in Figure 1. A factor loading of .4 was used for descriptive purposes to identify the region of variability in each of the

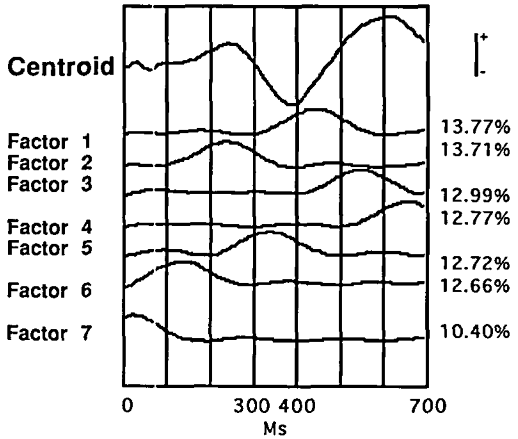

FIGURE 1 The group-averaged Centroid or grand average event-related potential of the entire data set and the factor loadings for each of the seven factors derived from the principal components analysis. The percentage of variance accounted for by each factor is displayed to the right of that factor. The time course is 700 ms with positivity up. The calibration marker is 5 mv.

factors. Thus, Factor 1, which accounted for 13.77% of the variance, rose above .4 at 370 ms poststimulus onset, reached its maximum value at 450 ms, and dropped below .4 at 530 ms post-onset. The region of greatest variability for Factor 2 (13.71% of the variance) began at 170 ms, peaked at 250 ms, and ended by 320 ms. Factor 3 (12.99% of the variance) was characterized by an increase at 480 ms, a peak at 550 ms, and a decline by 630 ms. Variability in Factor 4 (12.77% of the variance) rose above .4 at 280 ms, peaked at 350 ms, and declined by 420 ms. Factor 5 variability (12.72% of the variance) rose at 580 ms, peaked at 660 ms, and continued a high level through to the end of the sample at 700 ms. Increased variability was noted for Factor 6 (12.66% of the variance) to increase from 70 ms, peak at 140 ms, and decline by 210 ms. Finally, variability for Factor 7 (10.4% of the variance) began with stimulus onset, peaked at 30 ms, and declined below .4 at 100 ms poststimulus onset.

The PCA generated factor scores for each averaged ERP for each factor. Consequently, 3,834 factor scores were generated for Factor 1, which reflected the variability across each of the averaged ERPs for the three consonants (3), three vowels (3), six electrode sites (6), and 71 infants; a second set of 3,834 factor scores were generated for Factor 2, which identified variability in a different region of the averaged ERPs; a third set of 3,834 factor scores were generated for Factor 3, and so forth. These factor scores, which reflected the amount of variability for that factor in an individual ERP, constituted the dependent variables in a discriminant function analysis.

For the discriminant function procedure, two groups were established based upon their 5 year Stanford–Binet Verbal Reasoning subtest scores. Nine children with scores below 100 comprised the low group whereas 61 children with scores at or above 100 comprised the high group. The first set of discriminant analyses used scores obtained from Factor 2 (170–320 ms) to discriminate between the two groups of children. This latency window was selected because it had been identified earlier by D. L. Molfese and V. J. Molfese (1985) as discriminating infants at birth who 3 years later would be low or high language performers. Following the findings reported by D. L. Molfese and V. J. Molfese (1985), variables were selected for the discriminant function analysis that reflected consonant sound discrimination. Given the /b/–/g/ contrast that was employed, the ERP responses for these sounds were initially selected for this analysis. In addition, given that Molfese and Molfese reported both bilateral and lateralized effects related to later language skills, ERP factor scores reflecting these contrasts for both hemispheres were included. Finally, a decision was made to include temporal and parietal responses, given the general evidence of a posterior locus for speech and language perception.

The first discriminant function procedure used three difference scores derived from Factor 2 to discriminate the low from high performing infants. A difference score was obtained by subtracting the left temporal hemisphere factor score for /g/ initial syllables from those obtained for the left temporal hemisphere response to /b/ initial syllables (LTBG2). The second difference score was obtained for this same consonant contrast, although recorded from over the right temporal hemisphere (RTBG2). Finally, the third difference score was obtained by subtracting right hemisphere parietal factor scores obtained for /d/ initial syllables from those obtained at this electrode site from /b/ initial syllables (RPBD2). Thus, in all three cases the predictor variables involved difference scores derived from ERP responses to different consonant sounds. One significant function was successfully derived for these data, $\chi^2(3, N = 71) = 17.853, p < .0005, \Lambda = 7676$. This discriminant function, using these derived factor scores, was able to correctly classify 78.87% of the total sample (56 of 71 children). Seven of 9 children were correctly identified as belonging to the low group, whereas 49 of 62 children were correctly classified in the high group. The summary table for this discriminant function analysis is presented in Table 1. The differences between the two groups of children are illustrated in Figure 2, in which the auditory ERPs are presented for the two groups, averaged across electrode sites and stimulus conditions.

In Figure 2, the rectangle labeled 2 encloses the portion of the event-related potentials (ERPs) characterized by Factor 2. As can be seen in the figure, the

TABLE 1
Summary Tables for a Discriminant Function Using Three Variables

Step	*Variable Entered*	*Variables In*	*Wilks's Lambda*	*Function 1 Coefficients*
1	RTBG2*	1	.93513	0.93978
2	RPBD2**	2	.82497	0.57590
3	LTBG2***	3	.76760	−0.80863

*$p < .0321$. **$p < .0014$. ***$p < .005$.

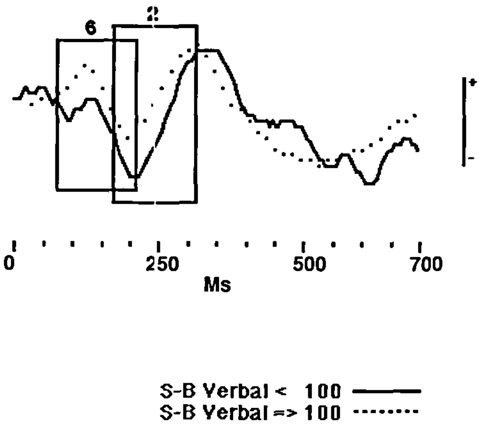

FIGURE 2 The newborn group-averaged auditory event-related potentials (ERPs) for the 9 children (solid line) who at 5 years of age scored below 100 on the Verbal Subtest of the Stanford–Binet and the 62 children (dotted line) who scored at or above 100 on that test. The time course is 700 ms with positivity up. The calibration marker is 5 mV. S–B = Stanford–Binet.

averaged ERP for the high group (dashed line) is more positive than that obtained for the low group (solid line). In addition, the overall amplitude of the large negative to positive shift within this window appears smaller for the high than the low group. This effect is further illustrated in Figure 3, which displays the left and right hemisphere frontal, temporal, and parietal ERPs. As in the preceding figure, the averaged ERPs represented within the Factor 2 rectangle are characterized by a more positive shift in polarity for the high group than for the low group. This effect can be noted across both hemispheres and across all electrode sites within each hemisphere.

In selecting the variables to include in the second discriminant function, a decision was made to include Factor 6 along with Factor 2, both of which covered the initial large negative peak earlier identified by D. L. Molfese and V. J. Molfese as discriminating high from low language performers. The original variables successfully used in the first discriminant function procedure were again selected, as were other variables from Factor 2, which also reflected consonant contrasts. In addition, factor scores reflecting ERP responses to vowel contrasts were included in light of the report by Molfese and Molfese that one ERP component was sensitive to such contrasts. The additional three variables obtained from Factor 6 included a difference score obtained by subtracting the right temporal hemisphere factor score for /g/ initial syllables from those obtained for the right temporal hemisphere response to /d/ initial syllables (RTDG2), a right hemisphere temporal response to the vowel /a/ (RTA6), and a difference in the way the two hemispheres responded to the /a/ versus /u/ vowels (HAU6). Thus, this discriminant function procedure used a total of six factor score derivatives to discriminate the low from high verbal performing children. This discriminant function was significant, $\chi^2(6, N = 71) = 37.98$, $p < .00001$, $\Lambda = .5624$. Using these six derived factor scores, classification accuracy rose to 91.55%, with a total of 65 of 71 children correctly classified (58

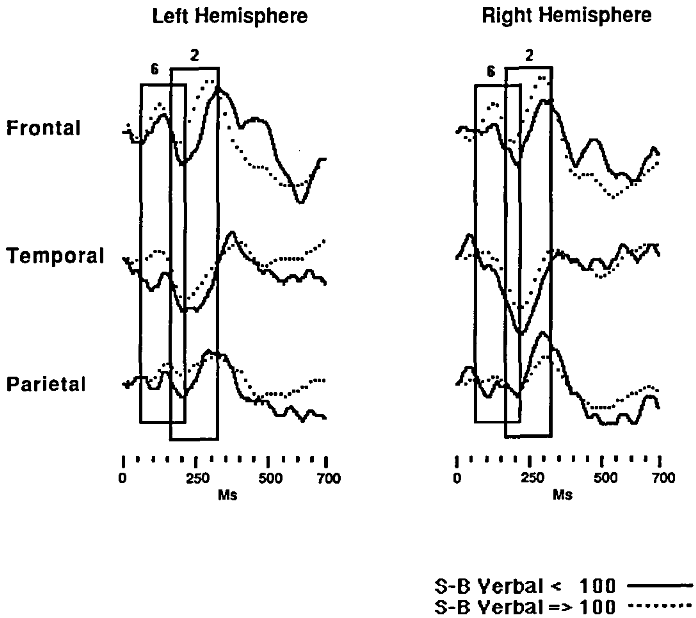

FIGURE 3 The newborn group-averaged auditory event-related potentials (ERPs) for the left and right hemisphere frontal, temporal, and parietal electrode sites obtained from the 9 children (solid line) who at 5 years of age scored below 100 on the Verbal Subtest of the Stanford–Binet and the 62 children (dotted line) who scored at or above 100 on that test. The time course is 700 ms with positivity up. The calibration marker is 5 mV. S–B = Stanford–Binet.

of 62 in the high group and 7 of 9 in the low group). However, no improvement was noted in correctly classifying the low group. The summary table for this discriminant function analysis is presented in Table 2. The differences in the ERPs are illustrated in Figures 2 and 3 as depicted within the rectangle labeled *6*. This region, which is part of Factor 6, covers an earlier portion of the ERP than that characterized by Factor 2. Here, as for Factor 2, the averaged ERP waveform is more positive for the high group of newborn infants (dashed line) than for the low group (solid line). This difference is true for both the overall group averages as depicted in Figure 2 as well as the group-averaged waveforms represented in Figure 3 for the two hemispheres and the three electrode sites within each hemisphere.

A third discriminant function was attempted with the derived factor scores used in the second discriminant function plus the factor score derived from the left hemisphere temporal response to the CV syllables ending in /a/. This discriminant function was significant, $\chi^2(7, N = 71) = 42.93, p < .00001, \Lambda = .5192$. This function correctly classified 95.77% of the sample or 68 of 71 children. Nearly all of the low group (8 of 9 for 88.9%) were correctly classified along with 60 of 62 children (96.8%) belonging to the high group. The results from this final discriminant function are presented in Table 3.

DISCUSSION

These results indicate that auditory ERPs recorded at birth can successfully discriminate the verbal performance of these same children 5 years later. These findings build upon those previously reported (D. L. Molfese & V. J. Molfese, 1985). In addition, these results demonstrate that predictive accuracy can extend through to 5 years of age, 2 years beyond that first demonstrated by Molfese and Molfese. In that earlier study, as reviewed previously, three regions of the ERP waveform discriminated between newborn infants who 3 years later would perform differently on a verbal performance task. This study utilized two of those three ERP

TABLE 2
Summary Tables for a Discriminant Function Using Six Variables

Step	*Variable Entered*	*Variables In*	*Wilks's Lambda*	*Function 1 Coefficients*
1	RTA6*	1	.89090	0.57217
2	HAU6**	2	.76600	0.62115
3	RTBG2***	3	.71490	0.57142
4	RPBD2***	4	.63011	–0.67502
5	LTBG2***	5	.58299	–0.45053
6	RTDG6***	6	.56242	–0.28587

*p = .00490. **p = .00010. ***p = .0001.

TABLE 3
Summary Tables for a Discriminant Function Using Seven Variables

Step	*Variable Entered*	*Variables In*	*Wilks's Lambda*	*Function 1 Coefficients*
1	RTA6*	1	.89090	0.57318
2	HAU6**	2	.76600	–0.46380
3	RTBG2***	3	.71490	–0.55169
4	RPBD2***	4	.63011	–0.94998
5	LTBG2***	5	.58299	0.74173
6	LTA6***	6	.54973	0.42114
7	RTDG6***	7	.51924	0.35001

*p = .00490. **p = .00010. ***p = .00001.

regions in its attempt to predict to later outcomes. Three related discriminant functions were developed. The first used three derivative scores obtained from one factor to construct a single discriminant function; a second discriminant function was then developed using six factor scores derived from two partially overlapping factors; a third discriminant function employed seven scores derived from these two factors. All three discriminant functions accurately discriminated low- from high-verbal performing children. As more variables were added, correct classification improved from below 80% to over 95%. Confirmation in this study of the findings from D. L. Molfese and V. J. Molfese (1985, 1993) regarding the use of neonatal ERPs to predict later language performance outcomes are especially intriguing when it is considered that different verbal performance measures were used across these studies. The McCarthy Verbal scores were used by D. L. Molfese and V. J. Molfese (1985) whereas the verbal scores derived from the Stanford–Binet were used in this study. Thus, given this ability to classify children across different performance measures, it appears that ERP factor scores obtained from similar brain regions can be effectively used to discriminate performance on different standardized tests and at different ages.

This study was able to accurately classify children's language performance on verbal tests based upon their birth measures despite a narrower range of verbal skills. Indeed, the children in this study showed a narrower range of scores than that shown by the children originally tested by D. L. Molfese and V. J. Molfese (1985). Children in the previous study were characterized by McCarthy verbal scores that ranged from 12–99, a range of approximately 9 SDs. For this sample, the ranges of Stanford–Binet verbal IQ scores extended from 80–129, a difference of approximately 5 SDs. Nevertheless, despite this relatively narrow range of scores, analyses of this sample showed high classification accuracy.

There were other extensions from the earlier study. D. L. Molfese and V. J. Molfese used ERPs recorded from only the left and right temporal regions, T3 and T4, whereas this study employed a total of six scalp recording sites, two of which were identical to those used in the original study. As in the previous study, factor scores derived from the temporal sites were important in discriminating between children with different levels of verbal skills. In fact, for the most part, the discriminative models in this study included ERPs recorded primarily from the temporal sites and comprised two of three components in the three variable model, four of six in the second model, and five of seven in the third model. However, factor scores derived from frontal and parietal leads improved the classification accuracy beyond that produced by the temporal sites alone. The ability of the right parietal region to discriminate between consonant sounds also contributed to the discrimination between variations in language skills. Another variable that collapsed electrode sites within each hemisphere and then subtracted the contribution of the right hemisphere from that of the left also contributed to this discrimination. A final variable that characterized a more general level of hemisphere difference related to vowel discrimination further served to improve the discrimination. Thus, overall, although ERPs recorded from over the temporal regions of the two hemispheres continued to play a prominent role in predicting later developmental outcomes, additional contributions were noted at other electrode sites.

The obvious question that arises from these results is why any type of measure, behavioral or brain, should discriminate 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 any environmental factors? Rather, we 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. 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 way. It is these fundamental differences in perceptual skills that set the stage for early detection of responses that influence verbal performance. This argument will be developed more fully in the next few paragraphs using VOT as an example.

VOT is a perceptual cue utilized to discriminate voiced from voiceless consonant sounds. American English speakers possess a perceptual boundary that allows them to normally discriminate voiced consonants (e.g., /b, d, g/) from voiceless consonants (e.g., /p, t, k/; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Stevens & Klatt, 1974). Perception of this cue appears to be perceptually based and utilizes the temporal distance between laryngeal pulsing (i.e., vocal fold vibration) and the onset of consonant release (i.e., the passage of air through the vocal tract). Young infants appear to have this ability, as Eimas, Siqueland, Jusczyk, and Vigorito (1971) demonstrated when they showed that young infants discriminate voiced from voiceless consonants along boundary lines similar to those of adult language users. This ability to discriminate between speech sounds at certain temporal delays does not appear to be limited to humans. Kuhl and Miller (1975, 1978) reported that chinchillas also discriminated stop consonant speech sounds at approximately this boundary. Morse, D. L. Molfese, Laughlin, Linnville, and Wetzel (1987) reported a similar finding with infant and 1-year-old rhesus monkeys. Thus, it is possible that this skill may be a property of the mammalian auditory system. Finally, this ability to discriminate sounds based on temporal delays is not limited to speech sounds. Pisoni (1977) and D. L. Molfese (1980) presented behavioral and electrophysiological data, respectively, showing that adults discriminate between nonspeech multiformant tones in a similar fashion. These electrophysiological findings were later replicated in adults by Segalowitz and Cohen (1989) and with 3-year-old children (D. L. Molfese & V. J. Molfese, 1988).

From this series of studies it appears likely that humans are able to utilize an inherent auditory perceptual ability to make speech-relevant phonetic distinctions.

However, what happens if auditory sensitivity to such an acoustic boundary as VOT is shifted away from the usual boundary for a particular child? A shift of only 30 ms would result in the infant hearing only one consonant sound across a range heard by most listeners as two different consonant sounds. The voiced and voiceless bilabial stop consonants produced by the parent would only be heard as a single (voiced) consonant sound. Instead of hearing a difference between the word *big* spoken by the parent when pointing to a large object versus *pig,* the infant might hear the word *big.* The objects or events would appear to the infant to have exactly the same label, *big.* Thus, there would be less invariance in the child's language environment and the ability to map from sound differences to word meaning differences would be impaired. Because half of the consonant sounds in American English are voiced, the potential exists that the infant could experience other voiced versus voiceless confusions as well. Although not all stop consonants have their voicing boundary at 30 ms, as in the case of the velar stops (e.g., /g/ vs. /k/) which have a boundary at approximately 40 ms, such a boundary shift could still affect other speech sound discriminations, lessening their distinctiveness.

Perhaps an even more difficult scenario is one in which the acoustic boundary is shifted just 10 ms. Thus, if the infant's boundary is at 40 ms instead of 30, the infant would most likely hear voiced consonants 75% of the time. Although the infant would have no difficulty in identifying correctly all of the voiced consonant exemplars (with VOT values at 20 ms), the voiceless tokens would be ambiguous and might force the infant to use a guessing strategy to classify the sound as voiced or voiceless. All of these factors could contribute to delays in the child's acquisition of some words or, at the very least, make the task of mapping from phonetic contrasts to meaning differences a much more formidable one. In the meantime, infants with a more normally tuned auditory system would hear more readily the phonetic difference between the two words pronounced by the adult and would begin to develop the different semantic links that characterize different sounding words. Because the task for normally hearing infants is not as formidable because of their ability to more readily hear the voicing differences, these infants can use their resources to advance in other areas, which advantages them further over infants with perceptual boundary problems.

Although the general belief has long existed that language perception is carried out by mechanisms largely restricted to the left hemisphere (Lenneberg, 1967), variables identified in this study that reflected ERP activity recorded over both the left and right hemispheres were used to successfully discriminate between populations of children with different levels of verbal performance. These findings support a position counter to that of Lenneberg 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. It is our belief at this time that these bilaterally represented mechanisms play a fundamental role in the development of verbal abilities.

Based on these results, which extend earlier reports, it appears that electrophysiological measures obtained at birth involving the auditory ERP can be used successfully to discriminate between infants who 5 years later will display different levels of verbal skills. This finding raises exciting possibilities regarding the early identification of children with potential language problems. This finding opens up the possibility that successful intervention of language problems could be carried out before these problems have become fully manifested in the child's behavior. At present, the identification of children with language and other cognitive problems occurs relatively late, often occurring in the elementary school years after it is established that the child is performing below grade level. One consequence of this delayed identification strategy is that it occurs so late in the child's overall cognitive and linguistic development. Thus, it may already be pushing the edge of the child's cognitive flexibility and its ability to master new skills. Witelson and Swallow (1988) noted that 10 years of age could mark an important transition or major breaking point in development because there are marked changes in abilities such as spatial pattern recognition, Braille, and map reading after this time. Others (Curtis, 1977) have shown that the onset of puberty appears to set limits on 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, the planned interventions could be introduced earlier to the child and, consequently, be more successful in remediating the child's emerging language or cognitive problems.

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