SINGLE-TRIAL ANALYSES OF DEVELOPMENTAL TRENDS IN INFANT AUDITORY EVENT-RELATED POTENTIALS

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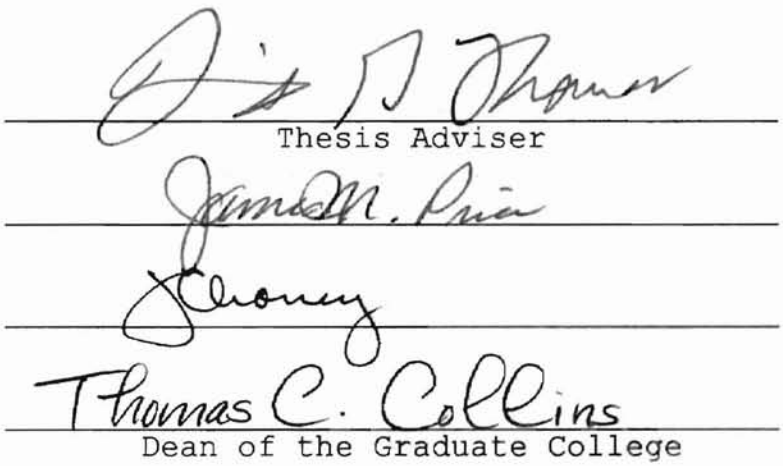

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PREFACE

This study was conducted to provide new insight into the developmental course of auditory event-related potentials (ERPs) in early infancy. Average ERP waveforms were compiled for twenty-four infants tested at three week intervals beginning at 5 weeks and concluding at 17 weeks of age. Specific objectives of this research were to (a) characterize developmental trends of the average ERP amplitude, single-trial amplitude, average latency, and trial-to-trial latency variability across the five ages, and (b) identify contributing factors to changes in the infant average ERP waveform.

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Abstract

Previous studies suggest that auditory ERP peak latencies show a general decrease while peak amplitudes show a general increase during development. In this study, event-related potentials (ERPs) were obtained from 24 infants at 5, 8, 11, 14, and 17 weeks of age. Auditory ERPs were recorded from frontal (Fz) and central (Cz) electrodes. Changes in the average ERP amplitude (components N1, P2, N2, and P3) were assessed in relation to latency variability and single-trial amplitude average. Results indicate significant developmental trends in average amplitude, average latency, latency variability, and single-trial amplitude. Changes in the average amplitude were primarily accounted for by single-trial amplitude and secondarily, but also significantly, by latency variability.

Single-trial Analyses of Developmental Trends in Infant Event-Related Potentials

USE AND MEASUREMENTS OF ERPS

Linking emerging psychological and behavioral functions with their underlying neural mechanisms is a growing domain of human developmental neuroscience. In order to obtain information about learning and cognitive processes within the developing human brain, research of this nature must rely primarily on the use of non-invasive techniques (Vaughan & Kurtzberg, 1992). Valuable information about brain functioning can be gleaned from the electrical activity generated extracellularly by neurons and manifested in the electroencephalogram (EEG). An EEG is a global assessment of underlying brain activity that provides a measure of the summed activity of hundreds or thousands of neurons. In humans, it is measured through electrode placement on the scalp, amplified, and displayed on a polygraph.

In order to more precisely determine underlying neural activity, an EEG can be recorded in relation to a sensory stimulus, cognitive event, or motor act. EEG recordings associated with discrete stimulus events are called event-related potentials or ERPs. ERPs are manifestations of the activity of large numbers of neurons, or neural ensembles, closely synchronized with the stimulus event. As such, they provide real time indices of brain processes.

More than eight different components of auditory ERPs have been identified in adults and are believed to represent different neurophysiological activity involved in cognitive processing (Courchesne, 1983). For example, in adults, N1 is related to selective attention while P2 is associated with early processing of the stimulus. N2 is related to target detection and reaction time while P3 is associated with memory updating (Polich, 1993). Although the same alpha-numeric labels are used to identify the components of the infant ERP waveform, assumptions concerning the underlying neurophysiological activity may or may not apply to infants (Thomas & Crow, 1994).

Given that ERPs reflect some aspects of neural ensemble functioning, they are extracted from the ongoing spontaneous electrical activity by averaging a number of EEG samples time-locked to the stimulus event. The electrical activity at each electrode is digitally sampled at rates which usually range from 100 Hz to 2000 Hz depending on the experimental requirements. Sampling windows may also range from 10 ms to several seconds. For example, an experiment might involve data collected at 250 Hz (input sampled every 4 ms) for 500 ms prior to and 1000 ms following stimulus onset. In an experiment consisting of 100 trials of a repetitive stimulus, the data for a given electrode consists of a two-dimensional array with M columns (data samples per trial; in this example M = 375) and N rows (representing the 100 trials). The procedure most commonly used, though not

the only alternative, is to calculate the average ERP by taking the mean value for each of the columns. This procedure, called signal averaging, accomplishes a reduction in data as well as an increase in the signal-to-noise ratio.

Studies which employ average ERPs typically disregard response variance as a descriptive statistic and view it as a nuisance. Because only the average waveforms are considered, trial-to-trial variability is disregarded (Thomas et al., in press). However, in a study with adults conducted by Thomas, Neer, and Price (1989), latency variability and single-trial average amplitude[1] were shown to account for almost all (90-99%) of the amplitude variance of N1 in the average ERP. In this case, latency variability was shown to play an important role in explaining the variance in the average amplitude. Average ERP amplitude and latency variability exhibit an inverse relationship as seen in Figure 1. Greater variability results in smaller average amplitudes, whereas lesser variability results in larger amplitudes (Thomas et al., 1989; Thomas & Lykins, 1995).

Estimating response variability can be done with methods derived from standard data processing procedures. Trial-to-trial latency variability represents the consistency of the electrical response to the stimulus in the temporal dimension. An estimate of the signal (the brain's response to the experimental stimulus) is derived from the average ERP, (Thomas et al., 1989) and is used as a

template which is moved across each single-trial waveform. The temporal point in the latter where the best match with the template occurs is designated as the latency of the signal in that trial. Latency variability is then estimated by the standard deviation of these single-trial latencies.

The role of latency variability in ERP measures of infant memory was examined by Thomas and Lykins (1995) in two experiments with 5-month-old infants. Infants were presented with 100 trials of a stimulus followed 24 hours later by a random presentation of 50 previously presented stimuli and 50 presentations of a single novel stimulus. Analyses confirmed a significant increase in average ERP amplitude for the familiar stimulus in comparison to the novel stimulus (stimuli experienced on the second day but not the first are designated as the novel stimuli) on the second day. The increase in average amplitude appeared to be due to both a significant decrease in latency variability and an actual increase in amplitude across days for the familiar stimulus.

ERPS IN INFANCY

Courchesne (1983) proposes that examination of age-related differences in the infant ERP waveform could provide a means of mapping developmental trends and transitions. Adequate assessment cannot be obtained from studies in which only one age-group of infants is studied. However, only a few studies have been designed to assess changes in ERP components associated with development and

these have all focused on the average ERP and have disregarded variability. Vaughan and Kurtzberg (1992) reported average ERPs from longitudinal data across nine ages from birth through the first year. Structure of the waveform recorded over the midline central region (Cz) became better defined and shorter in latency during the first six months. Maximum amplitude for auditory stimuli was achieved at 5 to 6 months. A study conducted by Kurtzberg, Hilpert, Kreuzer, and Vaughan (1984) yielded similar results indicating morphological waveform changes with peaks becoming more clearly differentiated and shorter in latency over the first three months of life. Of the developmental auditory ERP studies conducted, general findings support an increase in complexity (Barnet, Ohlrich, Weiss, & Shanks, 1975; Novak, Kurtzberg, Kreuzer, & Vaughan, 1989; and Shucard, Shucard, & Thomas, 1987), increase in amplitude (Barnet et al., 1975; Ohlrich & Barnet, 1972; Shucard et al., 1987, 1988), and decrease in latency (Barnet et al., 1975; Novak et al., 1989; Ohlrich & Barnet, 1972; Shucard et al., 1987, 1988; and Weitzman & Graziani, 1968).

These studies describe clearer definition and shorter latency of the ERP waveform as development proceeds. Such changes in latency are easily interpretable as changes in the processing speed of neural ensembles. However, changes in the average ERP peak amplitude are not as readily characterized. Postulated explanations include "true" amplitude increases possibly produced by changes in synaptic

strength or changes in the number of neurons responding to the stimuli, and/or latency variability changes reflected in the average amplitude rather than "true" increases in amplitude (Thomas et al., in press). Again, the effect of variations in latency on average amplitude can be clearly seen in Figure 1.

Although the research findings from 5-month-olds (Thomas & Lykins, 1995) address latency variability in a 24-hour memory paradigm, they do not address questions concerning its role in developmental ERP changes. The present study proposed to address these questions through analyses of developmental changes in the average ERP amplitude (components N1, P2, N2, & P3). These components were assessed in relation to latency variability and single-trial amplitude average over the first few months of life (5, 8, 11, 14, and 17 weeks of age). It was proposed that decreases in latency variability and/or increases in single-trial amplitude should account for variability in the average ERP. The overall relationship as well as the unique contribution of each of these measures was examined with an emphasis on the role of latency variability. In addition, trend analyses were utilized to assess developmental changes across the five ages for average ERP peak amplitude, single-trial amplitude, peak latency, and latency variability. Analyses of these data will aid the development of theoretical concepts of the contributing factors in average amplitude changes during early infancy.

Method

Subjects

Subjects were recruited from birth announcements published in the local newspaper. All infants tested were full-term, healthy infants with no known history of auditory or neurological problems. Data were collected at the ages of 5, 8, 11, 14, and 17 weeks. The mean age in days for each was 30.2, 53.0, 74.3, 95.6, and 117.2, respectively. Of 32 infants originally tested, data for eight subjects were discarded for the following reasons: the infant was not judged to be alert during stimulus presentation (n=3); the infant did not complete all sessions (n=3); or too few artifact-free trials were gathered (n=2). The final sample consisted of 24 infants (10 males, 14 females).

Stimuli

Infants received a series of tones and clicks at 5 weeks of age (one session for each stimulus type). Half of the infants then received clicks and the other half tones at ages 8, 11, and 14 weeks. All infants again underwent two separate sessions of tones and clicks at 17 weeks.

Infants received 64 presentations of a click (a 5 ms burst of variable length pulses) or 64 tones (100 ms, 400 Hz) depending on the experimental session. Auditory stimuli were presented binaurally over earphones adapted to fit securely over the infant's ears. The intensity of the tones was 70 dB sound pressure level at the earphone. Click

amplitude was matched to the 70 dB tone level by two adult observers who adjusted the perceived loudness of the clicks.

EEG Recording

The EEG was recorded through tin electrodes sewn into an elastic cap (Electro-Cap International). Three different cap sizes were used across the sessions to keep electrode placement consistent during development. Active electrodes were placed over midline posterior, central, and frontal scalp positions (Pz, Cz, and Fz, respectively, of the International 10-20 System, Jasper, 1958). Due to problems with electrode movement, data collection at Pz was discontinued part way through the study. The scalp electrodes were each referenced to the left earlobe with the forehead as ground. Eye movements (EOG) were monitored by miniature tin electrodes placed above and to the left of the left eye (Connolly & Kleinman, 1978). Impedances were kept below 10 Kohms.

EEG amplification was achieved by Grass Model 7P511 amplifiers with bandpasses of 1-100 Hz. EEG and EOG data were collected for 500 ms before and 1000 ms after stimulus presentation. The EEG was digitized and stored by the computer at a rate of one sample every 4 ms (250 Hz).

Procedure

Parents brought their infants to the laboratory at a time when they would be most alert and would nurse or take a bottle. The parent was seated in a reclining chair and held the infant on their lap. After informed consent was

received, the cap, eye and ear leads, and earphones were placed in approximately 20 minutes. The experimenter then withdrew to the control room for presentation of stimuli. Infants usually nursed or bottle fed during presentation to minimize movement. Infants were monitored via the EEG, EOG, and a video monitor. Communication with the parent was possible via an intercom. Stimuli were presented only when the infant appeared awake and not moving. Minimum inter-stimulus interval was 6 seconds while the maximum was dependent on movement. To be included in the study, infants had to be judged awake during all presentations of the stimuli by both the experimenter and the parent.

Infants received 64 presentations of either clicks or tones on their first visit to the laboratory at 5 weeks of age. An identical procedure, except that the infant received 64 presentations of the stimulus not previously presented, was repeated within a four day time period (order was counter- balanced across subjects). Infants were then randomly assigned to receive either 64 tones at 8, 11, and 14 weeks, or 64 clicks at these same ages. At 17 weeks of age, the infants returned to the laboratory twice during a four day period. They received either 64 tones or 64 clicks during the first session and the remaining stimulus during the second. For clarity, the stimulus that was heard at all five ages is referred to as the familiar stimulus and the stimulus presented only at 5- and 17-weeks the unfamiliar, or novel stimulus.

Data Processing

Each subject's raw data consisted of 64 single-trial ERPs from each of the five familiar stimulus presentations and the two unfamiliar stimulus presentations for electrodes Cz and Fz. Any trial in which any of the channels exceeded ±100 μV was discarded. The minimum number of trials used was 20. The single-trial waveforms were averaged and digitally low-pass filtered at 50 Hz. After data reduction, each subject's data consisted of average ERPs, single-trial amplitude averages, average peak latencies, and latency variability from the two electrodes for the familiar stimulus at 5, 8, 11, 14, and 17 weeks.

Average Peak amplitude. Peaks N1, P2, N2, and P3 in the average ERP evoked by auditory stimuli occurred at approximately 50-200 ms, 150-350 ms, 200-800 ms, and 300-1000 ms respectively post-stimulus, dependent upon developmental age (Barnet et al., 1975). Peak amplitude for each component (N1, P2, N2, and P3) at each developmental age (5, 8, 11, 14, and 17 weeks) was measured baseline-to-peak, with the baseline being the mean of the 500 ms pre-stimulus average, for the largest deflection within each respective latency period.

Latency variability A cross-correlational method described by Michalewski, Prasher, and Starr (1986) and Thomas et al. (1989) was used for single-trial analysis. Using the average ERP, a template was created for each peak of interest from the average ERP. The template for each

peak (N1, P2, and N2) consisted of 51 data points (200 ms) with the peak as the midpoint. The template was moved, point by point, across a 400 ms time window (200 ms before and after average peak latency) in each single trial waveform. A Pearson correlation coefficient was calculated for each successive set of 51 points. The point at which maximum correlation occurred was identified as the peak within that single-trial. Latency was then measured, with the standard deviation of the latency values used as an estimate of latency variability.

Peak P3 latency variability could not be derived from the individual average ERP peak latencies due to the late occurrence of this peak midpoint in early infancy. Although data collection continued for 1000 ms after stimulus presentation, Peak P3 ranged from 436-996 ms for ages 5 and 8 weeks and did not allow the 100 ms extension beyond the peak midpoint required by the template. With the 100 ms extension requirement, it was not possible to process latency variability or single-trial amplitude for peak P3.

Single-trial average amplitude. The template derived for each peak in determining latency variability was also utilized in calculating its single-trial average amplitude. When the point at which maximum correlation had been identified as the component (either N1, P2, and N2) within that single-trial, the amplitude was measured baseline-to-peak. The mean of the amplitude values across all trials was used as the single-trial average amplitude.

Similar to latency variability, P3 single-trial amplitude could not be processed due to its temporally delayed nature and the processing requirements of the template.

Results

Data analyses were performed separately for each of four components (N1, P2, N2, and P3), each of two electrodes (Cz, and Fz), and each of two stimuli (Tones, or Clicks). Developmental trends analyses, using data from all five ages, were performed for each of the four dependent measures: average ERP peak amplitude, average ERP peak latency, trial-to-trial latency variability, and single-trial average amplitude.

A second statistical focus was hierarchical regression analyses aimed at examining the role of latency variability (LATVAR) and single-trial amplitude (STA) in relation to changes in the average ERP amplitude (AERP). Again, these were performed separately for each peak, stimulus, and electrode. Initially, regression analyses were performed to assess the relationship of LATVAR and STA to the AERP obtained at each of the five ages. Then, difference scores (CHAERP) were computed in order to examine changes in average ERP amplitude across the five ages. For example, a difference score dependent variable was obtained when the average ERP amplitude at age five weeks was subtracted from the average amplitude at eight weeks. The same formula was used to calculate dependent measures between each of the remaining adjacent age categories (i.e., eight weeks from

eleven weeks, eleven weeks from fourteen weeks, and fourteen weeks from seventeen weeks). In addition, an identical formula was applied in calculating difference scores for both latency variability (CHLATV) and single-trial amplitude (CHSTA). These values were regressed on the change scores of the average ERP amplitude with latency variability's contribution assessed first. After latency variability was entered, single-trial amplitude's semi-partial correlation was assessed. These transformations allowed an examination of the contributing factors, change across time in latency variability and single-trial amplitude, to changes in the average ERP amplitude. Due to the temporally delayed occurrence of peak P3 in early infancy it was not possible to process latency variability or single-trial amplitude. Therefore, regression analyses were not employed for this peak. All analyses were performed with an N of 12 unless otherwise noted.

Average ERP peak amplitude

Tones. Table 1 gives mean values for each peak and electrode by stimulus. Although an increase in the average ERP amplitude was observed for peak N1 (N=5) at both electrodes Cz and Fz, trends analyses did not reach significance (see Figure 2). Figure 3 displays similar results that were obtained for P2. As shown in Figure 4, component N2 exhibited significant Quadratic trends at both electrodes Cz ($F[1,11]=4.84$, $p=.05$) and Fz ($F[1,11]=6.26$, $p=.029$). Significant increasing Linear trends were found for

peak P3 at both electrodes Cz ($F[1,11]=15.94$, $p=.002$) and Fz ($F[1,11]=11.35$, $p=.006$) and are shown in Figure 5.

Clicks. Figure 2 shows Trends analyses of N1 (N=7) which were not significant at either electrode site Cz or Fz. Component P2 revealed significant increasing Linear trends (see Figure 3) at both electrodes Cz ($F[1,11]=11.32$, $p=.006$) and Fz ($F[1,11]=5.11$, $p=.045$). As shown in Figure 4, significant Quadratic trends were found for peak N2 at both electrodes Cz ($F[1,11]=7.77$, $p=.018$) and Fz ($F[1,11]=5.64$, $p=.037$). Peak P3 exhibited increases in average amplitude at both sites Cz and Fz though neither reached the .05 significance level (see Figure 5).

Latency variability

Tones. Means and standard deviations for each peak and electrode by stimulus are given in Table 2. Peak N1 (N=5) exhibited a significant decreasing Linear trend at electrode Fz ($F[1,11]=7.97$, $p=.048$). A decreasing trend in latency variability was observed at electrode Cz but failed to reach significance (see Figure 6). For Peak P2, both electrodes (Cz and Fz) displayed nonsignificant decreases in latency variability. These trends are depicted in Figure 7. For N2, significant Linear trends, as illustrated in Figure 8, were identified at both electrode sites (Cz-$F[1,11]=6.60$, $p=.026$; Fz-$F[1,11]=6.76$, $p=.025$).

Clicks. Peak N1 (N=7) exhibited an increase in latency variability with a significant Quadratic trend identified at electrode Fz ($F[1,11]=6.35$, $p=.045$) but not at electrode Cz

(see Figure 6). No significant trends were identified for component P2 at either electrode although both displayed an increase in latency variability as can be seen in Figure 7. The same pattern of results was obtained for peak N2 (see Figure 8) with the exception that significance was reached at electrode Fz ($F[1,11]=12.46$, $p=.005$).

Single-trial amplitude

Tones. Means and standard deviations for Peaks N1, P2, and N2, by stimulus and electrode, are given in Table 3. As shown in Figure 9, N1 (N=5) exhibited a nonsignificant increase at electrode Cz while Fz displayed an increase only for weeks five through fourteen. A significant Quartic trend was identified at electrode Cz ($F[1,11]=5.64$, $p=.037$) for peak P2, while a significant increasing Linear trend was evident at Fz ($F[1,11]=8.46$, $p=.014$) (see Figure 10). This same pattern of results was also noted for peak N2 (Figure 11) with a significant Quartic trend at electrode Cz ($F[1,11]=6.38$, $p=.028$) and a significant Linear trend at Fz ($F[1,11]=5.44$, $p=.04$).

Clicks. As depicted in Figure 9, no significant trends were identified for component N1 (N=7). Significant increasing Linear trends were found for both electrodes Cz ($F[1,11]=24.40$, $p=.000$) and Fz ($F[1,11]=9.19$, $p=.011$) of peak P2 (see Figure 10). Analogous results were obtained for component N2 (Figure 11), electrode Cz ($F[1,11]=13.91$, $p=.003$) and Fz ($F[1,11]=7.82$, $p=.017$).

Average ERP peak latency

Tones. Table 4 gives mean values for each peak and electrode by stimulus. Analyses of components N1 and P2 did not reveal significant trends at either electrode site Cz or Fz (see Figs. 12 and 13 respectively). Analysis of peak N2 (Figure 14) revealed a significant decreasing Linear trend at electrode Cz ($F[1,11]=46.52$, $p<.001$) and Fz ($F[1,11]=36.53$, $p<.001$). Similar results were obtained for peak P3 (Figure 15), electrode Cz ($F[1,11]=20.20$, $p=.001$) and Fz ($F[1,11]=13.28$, $p=.004$).

Clicks. A significant Cubic trend was found at electrode Cz ($F[1,11]=7.09$, $p=.037$) for peak N1 (N=7). No significant trend was found at electrode Fz (Figure 12). At peak P2, a significant Quadratic trend (see Figure 13) was found at Cz ($F[1,11]=6.38$, $p=.028$) while Fz did not yield a significant trend. Although both electrodes of peak N2 exhibited decreases in latency, no significant trends were identified. These trends are depicted in Figure 14. As shown in Figure 15, P3 produced significant decreasing Linear trends at both electrodes Cz ($F[1,11]=4.94$, $p=.048$) and Fz ($F[1,11]=5.98$, $p=.033$).

Regression analyses

A series of hierarchical regression analyses by peak, electrode, and stimulus were employed to explore changes in the average ERP amplitude across five ages (5, 8, 11, 14, and 17 weeks of age). The first series of analyses examined the role of latency variability (LATVAR) and single-trial

amplitude (STA) in relation to the average ERP amplitude (AERP) at each of the five ages. Then, difference scores were computed for average ERP amplitude (CHAERP), latency variability (CHLATV), and single-trial amplitude (CHSTA). The next group of hierarchical regressions were performed with CHLATV and CHSTA regressed on CHAERP. Primary interest was in the role of CHLATV in the assessment of CHAERP. CHSTA was included next to determine if it contributed additional information. Overall relationships as well as unique contributions of each of the predictors was assessed at each of the five ages as well as for the difference scores.

Peak N1. Table 5 gives a summary of the multiple regression analyses for tone stimuli in which LATVAR and STA were used as predictors of AERP. Each table includes the proportion of unique variance contributed by the predictor along with its associated *F* value as well as the overall amount of variance accounted for by the regression model. Due to missing data at some ages, the N for each analysis is given. Overall, variance accounted for by LATVAR and STA ranged from 14-98% with STA generally accounting for more variance that LATVAR. Table 6 summarizes regression analyses of the change scores with CHLATV and CHSTA as predictors of CHAERP. Total variance accounted for ranged from 19-94%. Again, CHSTA outperformed CHLATV with the one exception at electrode Fz, change in age from 5 to 8 weeks.

Table 7 describes results from the regression analyses for click stimuli. Combined LATVAR and STA gave total

variances ranging from 47-93%. Similar to tones, STA accounted for more variance than did LATVAR. Results from multiple regressions utilizing difference scores for clicks at peak N1 are summarized in Table 8. Total variance accounted for by the regression models ranged from 50-87%. Akin to previous analyses, CHSTA outperformed CHLATV.

Peak P2. Table 9 gives a summary of regression analyses for tone stimuli at electrodes Cz and Fz. Results indicate that LATVAR and STA accounted for 20-91% of the variance in AERP. Unlike previous analyses reported, the role of LATVAR is more evident with it occasionally performing better than STA. Table 10 describes results for the difference scores with the predictors producing 21-86% variance accounted for in CHAERP. Similar to LATVAR, CHLATV sometimes outperformed CHSTA.

For peak P2 click stimuli, utilizing LATVAR and STA (see Table 11), variances extended from a low of 6.3% to a high of 88.7%. In these analyses, LATVAR's performance fluctuated with better performance at earlier ages. Analyses from the difference scores, supplied in Table 12, yielded results similar to previous findings. Variances accounted for ranged from approximately 23-89%. CHLATV and CHSTA exhibited alternating roles in explanation of the variance in CHAERP.

Peak N2. Table 13 gives a summary of the regression models from tone stimuli utilizing LATVAR and STA. These predictors accounted for approximately 24-96% of the

variance in AERP. LATVAR's performance fluctuated from age to age as well as from electrode to electrode. Table 14 summarizes the regressions from the difference scores with a range of variability accounted from 41.5% to 89%. Similar to LATVAR, CHLATV's performance fluctuated with better performance at electrode Cz.

As with tones, LATVAR and STA as derived from click stimuli accounted for approximately 15-84% of the variance in the click AERP (see Table 15). In general, STA performed better at younger ages while LATVAR performed better at later ages. Difference scores, as seen in Table 16, produced lower rates of variance accounted for (8.7-75%) with STA performing better except at electrode Fz, change from eleven to fourteen weeks of age.

Discussion

Analyses of the average ERP amplitude for both tones and clicks confirmed findings from previous studies (Thomas & Crow, 1994): Average amplitude increases as development proceeds. This was true for all but click-evoked stimuli at peak N1. However, increases in average amplitude proceeded in a linear fashion only for click stimuli at both electrodes of peak P2 and for tones (both electrodes) at peak P3. In general, the process was heterogeneous with increases and decreases across the five ages.

Also similar to previous findings, average ERP peak latency generally decreased from five to seventeen weeks for both stimuli at each peak. These trends were most evident in

peaks N2 and P3. Again, these decreases did not occur in a linear manner.

Exploration of single-trial amplitude trends indicated increasing amplitude though this did not always follow a linear course. Most notably, single-trial amplitude trends exhibited strong similarities to the average ERP amplitude trends.

In contrast, latency variability's course was inconsistent, but did exhibit some regularity across stimuli and peak. For tones, latency variability generally decreased from five to 17 weeks, while it increased for click stimuli. This would seem to indicate that the latency variability measure is sensitive to the type of experimental stimulus used as a function of age.

Though these developmental trends defy simple representation, they do confirm previous findings that average ERP amplitude increases while average latency decreases as development proceeds (Thomas & Crow, 1994). This, however, does not invariably occur in a linear fashion. The variability found across ages in the present study may represent bursts of neuronal branching and as such, indicates reorganization of neuronal ensembles. For both types of stimuli, as well as at each peak, latency variability begins to increase at 14 weeks of age. This coincides with previous research in brain growth spurts (Epstein, 1978) that has identified a growth spurt at approximately 3 months of age. As more neuronal connections

become available, the ensemble may explore new pathways. This conclusion gains support from single-trial amplitude analyses which also show an increase from fourteen to seventeen weeks independent of stimuli or peak.

In general, trend analyses confirm that average ERP amplitude and single-trial amplitude increase during development and that average ERP latency decreases. Latency variability's course fluctuates during development and was dependent on the experimental stimulus in this study. Since the findings for each stimulus differed, experience with the stimulus appeared to be shaping the neuronal ensemble.

In order to more fully understand the relationship among single-trial amplitude, latency variability, and the average ERP amplitude, regression analyses were undertaken. Previous results from adults have found that single-trial amplitude and latency variability account for almost all of the variance found in the average ERP amplitude (Thomas, Neer, & Price, 1989). The present study with infants aged 5 weeks to 17 weeks found lower levels of variance accounted for by single-trial amplitude and latency variability. And generally, single-trial amplitude performed better than latency variability. This was also true for analyses of the difference scores.

Several possible explanations exist that may clarify the reasons for the reduced performance of single-trial amplitude and latency variability in description of the infant average ERP waveform. These include the template

matching procedure, the enduring nature of infant memory, and the infant's level of stimulus experience.

A first potential explanation concerns the template matching procedure used to extract latency variability and single-trial amplitude. The template is derived from the average ERP waveform and is utilized in a search across a specified time window. A match is obtained when the highest correlation between template and the specified peak is reached. This results in a template comparison with the ERP peak based on shape rather than size. In this study, the matching procedure appears to have performed poorly. That is, it appears that noise, rather than the appropriate peak, was often correlated as highly with the template as was the signal. Since latency variability and single-trial average amplitude were obtained from this process, the introduction of noise resulted in a decreased ability of these two measures to adequately account for variance in the average ERP waveform.

This is clearly in contrast to previous findings from adults in which latency variability and single-trial amplitude accounted for nearly all (90-99%) of the variance in the average ERP waveform. With this infant ERP data, the introduction of noise rendered the template matching procedure less effective. However, this does not preclude the validity of the procedure for use in future infant studies. This is more fully elucidated in the second

possible explanation which concerns the duration of memory in early infancy.

In the present study, experimental sessions were conducted at three week intervals beginning at 5 weeks of age and concluding at 17 weeks of age. However, Rovee-Collier and Sullivan's (1980) investigations have found that infant memory at 3-months-of-age only endures for approximately two weeks with shorter duration intervals at younger ages. Thus, the three week interval utilized in this study was unable to capitalize on the organizing effects of repeated experience.

This brings us to a third possible explanation concerning the role of experience. Previous studies (Thomas & Lykins, 1995) have found that increased experience with a stimulus serves to increase the consistency of the response to that stimulus (e.g. decrease in latency variability) as well as increase the amplitude. As was outlined in the introduction, an increase in response consistency results in a better defined waveform. With a more consistent and larger response, the template matching procedure performs acceptably. This has previously been demonstrated with adult waveforms.

In general, the template matching procedure did not perform as well with these infant waveforms as it did with the adult waveform. Alternatives to the template used in this study could include the whole waveform, or half of the peak rather than the whole peak. This may serve to adjust

for the less consistent neuronal responses in early infancy. Another aspect of template development should include the development of a criterion with respect to the efficiency of the template used. The criterion would provide a measure of assessment in determining a useful template for single trial analysis in infant research. These are empirical questions that can be answered in future research designs. However, decreased performance may also have resulted from the infant's inadequate experience with the stimulus and the length of time between experimental sessions.

The present study confirms previous findings of increased average amplitude as well as decreased average latency. However, subsequent analyses of the factors contributing to the average ERP amplitude found that single-trial amplitude played a more significant role in increases found in the average amplitude. In contrast, latency variability's contribution was generally negligible. Overall, the amount of variance accounted for fluctuated between stimuli, age, peaks, and electrodes.

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prematurely born infant. Developmental Psychobiology, 1, 79-89.

Footnote

[1]A single-trial average is derived by measuring the amplitude of a given peak in each individual trial and then calculating its mean.

Table 1

Means and Standard Deviations (in parenthesis) of Average ERP Amplitude (μV) for Tones and Clicks by Age, Peak, and Electrode

	Average Amplitude				
	Tones				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	- .54	-1.64	-2.62	-3.10	-4.45
	(1.87)	(6.21)	(3.53)	(3.24)	(6.23)
Fz	.07	-3.06	-1.86	-2.96	- .42
	(3.37)	(7.77)	(3.47)	(2.61)	(6.70)
P2					
Cz	7.69	6.21	12.98	9.15	9.15
	(2.31)	(3.72)	(8.47)	(5.92)	(6.38)
Fz	7.50	6.11	10.58	10.22	10.36
	(2.26)	(3.70)	(5.21)	(5.70)	(7.31)
N2					
Cz	-6.87	-9.12	-11.96	-9.65	-9.75
	(1.99)	(3.80)	(6.08)	(7.35)	(6.30)
Fz	-7.21	-8.64	-10.19	-10.01	-8.06
	(2.51)	(2.97)	(5.04)	(7.66)	(4.97)

Table 1 (cont.)

P3					
Cz	2.82	3.87	4.79	5.78	9.63
	(2.58)	(6.27)	(2.88)	(3.42)	(6.56)
Fz	2.55	3.23	5.26	6.40	9.85
	(2.29)	(5.20)	(3.12)	(4.01)	(7.61)

	Clicks				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	-1.53	-2.33	- .95	-3.08	- .44
	(3.93)	(2.22)	(3.35)	(6.89)	(6.11)
Fz	-3.85	-3.29	- .83	-2.61	3.20
	(5.63)	(4.38)	(4.42)	(6.36)	(7.27)
P2					
Cz	4.53	5.39	4.86	6.83	6.94
	(5.08)	(5.17)	(3.55)	(4.99)	(4.37)
Fz	4.16	5.56	5.71	6.28	8.33
	(5.68)	(3.56)	(3.14)	(5.46)	(4.37)

Table 1 (cont.)

N2					
Cz	-6.05	-5.48	-4.69	-4.98	-9.51
	(3.43)	(3.11)	(2.62)	(3.67)	(7.11)
Fz	-5.97	-5.92	-4.33	-4.83	-8.65
	(3.82)	(2.42)	(2.92)	(3.64)	(7.46)
P3					
Cz	5.22	4.95	5.02	5.67	6.88
	(2.58)	(3.75)	(2.99)	(3.04)	(3.95)
Fz	5.27	4.77	4.71	6.04	5.92
	(3.16)	(2.84)	(3.32)	(3.55)	(3.72)

Table 2

Means and Standard Deviations (in parenthesis) of Latency Variability for Tones and Clicks by Age, Peak, and Electrode

	Latency Variability				
	Tones				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	68.05	65.42	59.39	60.95	61.93
	(3.03)	(4.15)	(6.86)	(12.69)	(10.21)
Fz	68.12	67.04	62.84	62.26	64.07
	(2.48)	(5.26)	(4.45)	(4.03)	(8.10)
P2					
Cz	61.45	61.68	56.09	56.71	57.90
	(3.10)	(6.03)	(10.50)	(10.39)	(9.37)
Fz	60.30	63.14	59.42	55.90	57.33
	(3.67)	(6.54)	(5.98)	(10.76)	(6.53)
N2					
Cz	64.18	63.16	59.44	57.31	57.43
	(3.39)	(5.55)	(7.36)	(5.99)	(10.14)
Fz	63.31	60.91	60.05	55.52	57.99
	(4.07)	(6.50)	(8.13)	(9.53)	(5.77)

Table 2 (cont.)

	Clicks				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	65.26	59.54	64.76	64.12	67.44
	(9.70)	(6.66)	(6.82)	(6.73)	(4.82)
Fz	67.71	62.42	61.93	64.68	68.41
	(4.87)	(5.51)	(8.75)	(6.20)	(5.14)
P2					
Cz	60.34	62.80	63.25	63.95	65.22
	(9.28)	(6.52)	(6.33)	(5.99)	(5.68)
Fz	62.75	63.90	62.38	62.83	64.99
	(9.83)	(8.33)	(5.07)	(6.20)	(5.47)
N2					
Cz	61.59	63.66	62.74	64.49	65.63
	(5.26)	(5.12)	(5.33)	(5.43)	(5.04)
Fz	60.09	63.05	63.31	65.58	66.42
	(6.90)	(7.93)	(5.76)	(3.20)	(5.33)

Table 3

Means and Standard Deviations (in parenthesis) of Single-trial Amplitude for Tones and Clicks by Age, Peak, and Electrode

Single-trial Amplitude					
	Tones				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	-7.29	-1.05	-13.85	-7.79	-13.88
	(4.22)	(17.69)	(6.35)	(3.25)	(5.79)
Fz	-4.85	-6.88	-9.99	-9.37	-2.97
	(4.37)	(17.56)	(5.58)	(4.18)	(14.76)
P2					
Cz	15.98	16.92	23.40	17.39	21.45
	(4.64)	(3.40)	(8.07)	(6.70)	(13.72)
Fz	13.97	13.45	19.21	17.80	22.65
	(3.58)	(7.57)	(4.38)	(5.23)	(11.00)
N2					
Cz	-15.67	-19.81	-24.34	-17.77	-22.49
	(3.29)	(6.70)	(6.25)	(10.39)	(8.35)
Fz	-15.28	-18.29	-21.46	-17.52	-20.89
	(3.21)	(4.67)	(4.45)	(8.15)	(6.26)

Table 3 (cont.)

	Clicks				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	-7.53	-12.04	-7.49	-9.66	-15.26
	(4.36)	(5.24)	(7.58)	(11.12)	(16.28)
Fz	-10.01	-13.20	-7.25	-7.36	-6.14
	(9.62)	(6.85)	(8.33)	(12.03)	(19.03)
P2					
Cz	9.62	14.65	13.10	19.84	21.95
	(8.50)	(6.21)	(10.06)	(7.51)	(8.59)
Fz	8.77	14.21	15.55	17.74	20.53
	(11.05)	(5.42)	(6.77)	(7.39)	(9.43)
N2					
Cz	-14.90	-14.28	-15.91	-17.56	-24.93
	(5.65)	(6.69)	(3.87)	(5.28)	(6.98)
Fz	-13.34	-15.28	-14.39	-15.70	-23.14
	(8.01)	(4.18)	(4.29)	(6.19)	(10.01)

Table 4

Means and Standard Deviations (in parenthesis) of Average ERP Latency (ms) for Tones and Clicks by Age, Peak, and Electrode

	Average Latency				
	Tones				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	88	96	108	116	136
	(33.6)	(34.9)	(67.1)	(38.2)	(27.7)
Fz	94	80	114	99	123
	(36.3)	(38.1)	(38.8)	(26.4)	(38.1)
P2					
Cz	228	228	256	232	222
	(44.3)	(33.0)	(30.5)	(38.1)	(39.2)
Fz	242	230	230	217	217
	(46.3)	(26.3)	(36.4)	(33.5)	(37.5)
N2					
Cz	560	540	492	430	358
	(112.5)	(108.5)	(81.6)	(87.4)	(82.9)
Fz	569	488	501	410	360
	(96.9)	(98.2)	(82.6)	(101.2)	(68.4)

Table 4 (cont.)

P3					
Cz	862	839	811	700	565
	(93.6)	(141.8)	(143.9)	(167.7)	(149.0)
Fz	813	807	777	690	567
	(92.4)	(163.1)	(121.1)	(175.3)	(201.9)

	Clicks				
Peak	5weeks	8weeks	11weeks	14weeks	17weeks
N1					
Cz	95	126	131	100	99
	(37.6)	(15.1)	(23.1)	(22.4)	(27.1)
Fz	114	104	115	102	110
	(44.1)	(38.4)	(36.5)	(25.2)	(23.7)
P2					
Cz	207	214	222	230	193
	(34.8)	(26.8)	(51.1)	(69.5)	(50.6)
Fz	244	235	227	206	236
	(52.3)	(32.5)	(51.2)	(61.3)	(75.2)

Table 4 (cont.)

N2					
Cz	447	494	478	435	428
	(119.4)	(122.2)	(140.7)	(151.9)	(126.2)
Fz	457	507	456	425	453
	(128.8)	(136.9)	(117.3)	(128.5)	(112.1)
P3					
Cz	770	834	785	710	736
	(125.7)	(143.2)	(138.0)	(131.9)	(130.5)
Fz	796	829	750	765	693
	(170.6)	(143.2)	(147.5)	(136.8)	(128.5)

Table 5

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N1			
Tones	Age	Variable	sr^2	F value	R^2	F value
Cz	5[a]	LATVAR	.016	.08		
		STA	.119	.55	.136	.31
	8[b]	LATVAR	.029	.21		
		STA	.623	10.75*	.652	5.62*
	11[c]	LATVAR	.082	.63		
		STA	.893	213.90**	.975	116.78**
	14[d]	LATVAR	.554	7.44*		
		STA	.255	6.67*	.809	10.58*
	17[e]	LATVAR	.213	2.70		
		STA	.137	1.90	.350	2.42
Fz	5[f]	LATVAR	.005	.03		
		STA	.690	11.31*	.695	5.70
	8[g]	LATVAR	.331	2.97		
		STA	.504	15.22*	.835	12.62*
	11[h]	LATVAR	.254	2.72		
		STA	.521	16.20**	.775	12.04**
	14[i]	LATVAR	.171	1.45		
		STA	.473	7.98*	.644	5.43*

Table 5 (cont.)

	17^{j}	LATVAR	.072	.77	
		STA	.441	8.14	.513	4.73*

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

$^{a}n = 7$. $^{b}n = 9$. $^{c}n = 9$. $^{d}n = 8$. $^{e}n = 12$. $^{f}n = 8$. $^{g}n = 8$. $^{h}n = 10$. $^{i}n = 9$. $^{j}n = 12$.

* $p < .05$; ** $p < .01$

Table 6

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

Tones	Age	Variable	Peak N1 sr^2	F value	R^2	F value
Cz	5 to 8 wks[a]	CHLATV	.140	.65		
		CHSTA	.653	9.43	.792	5.73
	8 to 11 wks[b]	CHLATV	.116	.79		
		CHSTA	.823	68.05**	.940	38.84**
	11 to 14 wks[c]	CHLATV	.273	1.87		
		CHSTA	.623	23.91**	.896	17.18**
	14 to 17 wks[d]	CHLATV	.077	.50		
		CHSTA	.116	.72	.193	.60
Fz	5 to 8 wks[e]	CHLATV	.492	2.91		
		CHSTA	.194	1.24	.687	2.19
	8 to 11 wks[f]	CHLATV	.300	2.57		
		CHSTA	.628	43.69**	.928	32.29**
	11 to 14 wks[g]	CHLATV	.080	.52		
		CHSTA	.358	3.18	.438	1.95
	14 to 17 wks[h]	CHLATV	.000	.00		
		CHSTA	.595	8.82*	.595	4.41

Table 6 (cont.)

Note. CHLATV = change between ages in latency variability; CHSTA = change between ages in single-trial amplitude; CHAERP = change between ages in average ERP amplitude.

$^{a}n = 6$. $^{b}n = 8$. $^{c}n = 7$. $^{d}n = 8$. $^{e}n = 5$. $^{f}n = 8$. $^{g}n = 8$. $^{h}n = 9$.

* = $p < .05$; ** = $p < .01$

Table 7

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N1			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5[a]	LATVAR	.124	1.14		
		STA	.651	20.34**	.776	12.11**
	8[b]	LATVAR	.218	2.51		
		STA	.378	7.47*	.596	5.89*
	11[c]	LATVAR	.001	.01		
		STA	.640	16.03**	.641	8.02**
	14[d]	LATVAR	.002	.01		
		STA	.865	51.65**	.866	25.87**
	17[e]	LATVAR	.047	.44		
		STA	.692	21.23**	.739	11.34**
Fz	5[f]	LATVAR	.042	.35		
		STA	.883	82.95**	.925	43.46**
	8[g]	LATVAR	.204	2.30		
		STA	.263	3.94	.466	3.49
	11[h]	LATVAR	.121	1.37		
		STA	.657	26.65**	.778	15.77**
	14[i]	LATVAR	.041	.34		
		STA	.653	14.91**	.694	7.92*

Table 7 (cont.)

	17^{j}	LATVAR	.395	6.54*	
		STA	.426	21.38**	.821	20.62**

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

^{a}n = 10. ^{b}n = 11. ^{c}n = 12. ^{d}n = 11. ^{e}n = 11. ^{f}n = 10. ^{g}n = 11. ^{h}n = 12. ^{i}n = 10. ^{j}n = 12.

* $p < .05$; ** $p < .01$

Table 8

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N1			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5 to 8 wks[a]	CHLATV	.369	4.09		
		CHSTA	.231	3.46	.600	4.49
	8 to 11 wks[b]	CHLATV	.022	.20		
		CHSTA	.718	22.07**	.740	11.37**
	11 to 14 wks[c]	CHLATV	.002	.02		
		CHSTA	.777	28.07**	.777	14.07**
	14 to 17 wks[d]	CHLATV	.000	.00		
		CHSTA	.502	7.05*	.502	3.53
Fz	5 to 8 wks[e]	CHLATV	.016	.12		
		CHSTA	.670	12.80*	.686	6.56*
	8 to 11 wks[f]	CHLATV	.006	.05		
		CHSTA	.505	8.25*	.510	4.17
	11 to 14 wks[g]	CHLATV	.006	.05		
		CHSTA	.864	46.66**	.870	23.49**
	14 to 17 wks[h]	CHLATV	.013	.11		
		CHSTA	.614	11.53*	.627	5.89*

Table 8 (cont.)

Note. CHLATV = change between ages in latency variability; CHSTA = change between ages in single-trial amplitude; CHAERP = change between ages in average ERP amplitude.

$^{a}n = 9$. $^{b}n = 11$. $^{c}n = 11$. $^{d}n = 10$. $^{e}n = 9$. $^{f}n = 11$. $^{g}n = 10$. $^{h}n = 10$.

* = $p < .05$; ** = $p < .01$

Table 9

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak P2			
Tones	Age	Variable	sr^2	F value	R^2	F value
Cz	5	LATVAR	.082	.89		
		STA	.755	41.59**	.837	23.05**
	8	LATVAR	.001	.01		
		STA	.541	10.62**	.542	5.32*
	11	LATVAR	.646	18.21**		
		STA	.266	27.09**	.912	46.41**
	14	LATVAR	.546	12.05**		
		STA	.307	18.88**	.854	26.24**
	17	LATVAR	.340	5.15*		
		STA	.323	8.63*	.663	8.86**
Fz	5	LATVAR	.014	.14		
		STA	.488	8.81*	.502	4.53*
	8	LATVAR	.348	5.33*		
		STA	.436	18.07**	.783	16.25**
	11	LATVAR	.155	1.83		
		STA	.040	.45	.195	1.09
	14	LATVAR	.412	6.99*		
		STA	.227	5.64*	.638	7.94**

Table 9 (cont.)

	17	LATVAR	.138	1.60	
		STA	.734	51.56**	.872	30.64**

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

* p < .05; ** p < .01

Table 10

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

Tones	Age	Peak P2 Variable	sr^2	F value	R^2	F value
Cz	5 to 8 wks	CHLATV	.003	.03		
		CHSTA	.572	12.13**	.575	6.10*
	8 to 11 wks	CHLATV	.327	4.86		
		CHSTA	.523	31.37**	.850	25.49
	11 to 14 wks	CHLATV	.488	9.53*		
		CHSTA	.376	24.88**	.864	28.59**
	14 to 17 wks	CHLATV	.544	11.95**		
		CHSTA	.126	3.43	.670	9.14**
Fz	5 to 8 wks	CHLATV	.187	2.30		
		CHSTA	.548	18.64**	.735	12.49**
	8 to 11 wks	CHLATV	.062	.66		
		CHSTA	.148	1.69	.210	1.20
	11 to 14 wks	CHLATV	.373	5.94*		
		CHSTA	.000	.00	.373	2.68
	14 to 17 wks	CHLATV	.032	.34		
		CHSTA	.822	50.91**	.855	26.46**

Table 10 (cont.)

Note. CHLATV = change between ages in latency variability;

CHSTA = change between ages in single-trial amplitude;

CHAERP = change between ages in average ERP amplitude.

* = $p < .05$; ** = $p < .01$

Table 11

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak P2			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5	LATVAR	.639	17.69**		
		STA	.248	19.76**	.887	35.31**
	8	LATVAR	.305	4.39		
		STA	.477	19.65**	.782	16.12**
	11	LATVAR	.265	3.61		
		STA	.458	14.88**	.723	11.75**
	14	LATVAR	.393	6.49*		
		STA	.303	8.98*	.696	10.33**
	17	LATVAR	.002	.02		
		STA	.061	.59	.063	.30
Fz	5	LATVAR	.535	11.49**		
		STA	.296	15.73**	.831	22.08**
	8	LATVAR	.206	2.59		
		STA	.374	8.01*	.580	6.21*
	11	LATVAR	.024	.24		
		STA	.521	10.29**	.544	5.38*
	14	LATVAR	.449	8.16*		
		STA	.389	21.69**	.839	23.37**

Table 11 (cont.)

	17	LATVAR	.056	.59	
		STA	.157	1.80	.213	1.22

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

* $p < .05$; ** $p < .01$

Table 12

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak P2			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5 to 8 wks	CHLATV	.530	11.27**		
		CHSTA	.361	29.89**	.891	36.85**
	8 to 11 wks	CHLATV	.081	.88		
		CHSTA	.260	3.54	.340	2.32
	11 to 14 wks	CHLATV	.038	.40		
		CHSTA	.222	2.70	.260	1.58
	14 to 17 wks	CHLATV	.077	.83		
		CHSTA	.152	1.78	.229	1.34
Fz	5 to 8 wks	CHLATV	.321	4.72		
		CHSTA	.497	24.54**	.818	20.20**
	8 to 11 wks	CHLATV	.184	2.25		
		CHSTA	.498	14.06**	.681	9.62**
	11 to 14 wks	CHLATV	.201	2.52		
		CHSTA	.144	1.97	.345	2.37
	14 to 17 wks	CHLATV	.234	3.06		
		CHSTA	.145	2.10	.379	2.75

Table 12 (cont.)

Note. CHLATV = change between ages in latency variability;

CHSTA = change between ages in single-trial amplitude;

CHAERP = change between ages in average ERP amplitude.

* = $p < .05$; ** = $p < .01$

Table 13

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N2			
Tones	Age	Variable	sr^2	F value	R^2	F value
Cz	5	LATVAR	.009	.09		
		STA	.230	2.72	.239	1.41
	8	LATVAR	.000	.00		
		STA	.502	9.07*	.502	4.54*
	11	LATVAR	.519	10.81**		
		STA	.362	27.39**	.881	33.34**
	14	LATVAR	.580	13.80**		
		STA	.219	9.82*	.799	17.90**
	17	LATVAR	.106	1.19		
		STA	.671	27.13**	.777	15.71**
Fz	5	LATVAR	.066	.71		
		STA	.756	38.37**	.823	20.87**
	8	LATVAR	.676	20.90**		
		STA	.187	12.57**	.865	28.84**
	11	LATVAR	.431	7.58*		
		STA	.442	31.18**	.873	30.81**
	14	LATVAR	.060	.64		
		STA	.903	217.27**	.963	115.85**

Table 13 (cont.)

17	LATVAR	.012	.13		
	STA	.557	11.62**	.569	5.94*

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

* $p < .05$; ** $p < .01$

Table 14

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N2			
Tones	Age	Variable	sr^2	F value	R^2	F value
Cz	5 to 8 wks	CHLATV	.307	4.43		
		CHSTA	.107	1.65	.415	3.19
	8 to 11 wks	CHLATV	.306	4.40		
		CHSTA	.413	13.17**	.718	11.46**
	11 to 14 wks	CHLATV	.356	5.53*		
		CHSTA	.298	7.76*	.654	8.51**
	14 to 17 wks	CHLATV	.308	4.54		
		CHSTA	.273	5.88*	.582	6.26*
Fz	5 to 8 wks	CHLATV	.292	4.12		
		CHSTA	.518	24.47**	.810	19.13**
	8 to 11 wks	CHLATV	.539	11.71**		
		CHSTA	.098	2.44	.638	7.92**
	11 to 14 wks	CHLATV	.119	1.35		
		CHSTA	.771	63.28**	.890	36.52**
	14 to 17 wks	CHLATV	.188	2.31		
		CHSTA	.676	44.54**	.864	28.47**

Table 14 (cont.)

Note. CHLATV = change between ages in latency variability;

CHSTA = change between ages in single-trial amplitude;

CHAERP = change between ages in average ERP amplitude.

* = $p < .05$; ** = $p < .01$

Table 15

Summary of Multiple Regressions of LATVAR and STA onto AERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N2			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5	LATVAR	.018	.18		
		STA	.727	25.65**	.745	13.14**
	8	LATVAR	.089	.98		
		STA	.149	1.76	.238	1.40
	11	LATVAR	.091	1.00		
		STA	.275	3.91	.367	2.60
	14	LATVAR	.020	.20		
		STA	.440	7.33*	.460	3.83
	17	LATVAR	.123	1.41		
		STA	.074	.83	.197	1.11
Fz	5	LATVAR	.003	.03		
		STA	.732	24.80**	.734	12.45**
	8	LATVAR	.018	.18		
		STA	.129	1.36	.147	.78
	11	LATVAR	.101	1.13		
		STA	.348	5.67*	.449	3.66
	14	LATVAR	.554	12.42**		
		STA	.285	15.94**	.839	23.46**

Table 15 (cont.)

17	LATVAR	.546	12.04**		
	STA	.146	4.28	.693	10.14**

Note. LATVAR = latency variability; STA = single-trial amplitude; AERP = average ERP amplitude.

* $p < .05$; ** $p < .01$

Table 16

Summary of Multiple Regressions of CHLATV and CHSTA onto CHAERP by Age (in weeks) and Electrode (Cz, Fz)

			Peak N2			
Clicks	Age	Variable	sr^2	F value	R^2	F value
Cz	5 to 8 wks	CHLATV	.050	.53		
		CHSTA	.332	4.84	.382	2.79
	8 to 11 wks	CHLATV	.000	.00		
		CHSTA	.225	2.61	.225	1.31
	11 to 14 wks	CHLATV	.061	.65		
		CHSTA	.026	.26	.087	.43
	14 to 17 wks	CHLATV	.000	.00		
		CHSTA	.108	1.09	.108	.54
Fz	5 to 8 wks	CHLATV	.004	.04		
		CHSTA	.630	15.45**	.633	7.78**
	8 to 11 wks	CHLATV	.037	.38		
		CHSTA	.289	3.86	.326	2.17
	11 to 14 wks	CHLATV	.408	6.90*		
		CHSTA	.342	12.33**	.750	13.53**
	14 to 17 wks	CHLATV	.080	.87		
		CHSTA	.386	6.50*	.466	3.92

Table 16 (cont.)

Note. CHLATV = change between ages in latency variability;

CHSTA = change between ages in single-trial amplitude;

CHAERP = change between ages in average ERP amplitude.

* = $p < .05$; ** = $p < .01$

Figure Captions

Figure 1. Representation of the influence of single-trial variability on average waveform amplitude. No variability results in larger amplitude (left panel), high variability in lower amplitude (center), and moderate variability in an intermediate level of amplitude (right). From "Event-related potential measures of 24-hour retention in 5-month-old infants," by D.G. Thomas and M.S. Lykins, 1995, Developmental Psychology.

Figure 2. Mean N1 peak amplitude across ages for tones and clicks at Cz and Fz.

Figure 3 Mean P2 peak amplitude across ages for tones and clicks at Cz and Fz.

Figure 4. Mean N2 peak amplitude across ages for tones and clicks at Cz and Fz.

Figure 5. Mean P3 peak amplitude across ages for tones and clicks at Cz and Fz.

Figure 6. Peak N1 trial-to-trial latency variability measured in standard deviation units.

Figure 7. Peak P2 trial-to-trial latency variability measured in standard deviation units.

Figure 8. Peak N2 trial-to-trial latency variability measured in standard deviation units.

Figure 9. Peak N1 single-trial average amplitude across ages for tones and clicks at Cz and Fz.

Figure 10. Peak P2 single-trial average amplitude across ages for tones and clicks at Cz and Fz.

Figure 11. Peak N2 single-trial average amplitude across ages for tones and clicks at Cz and Fz.

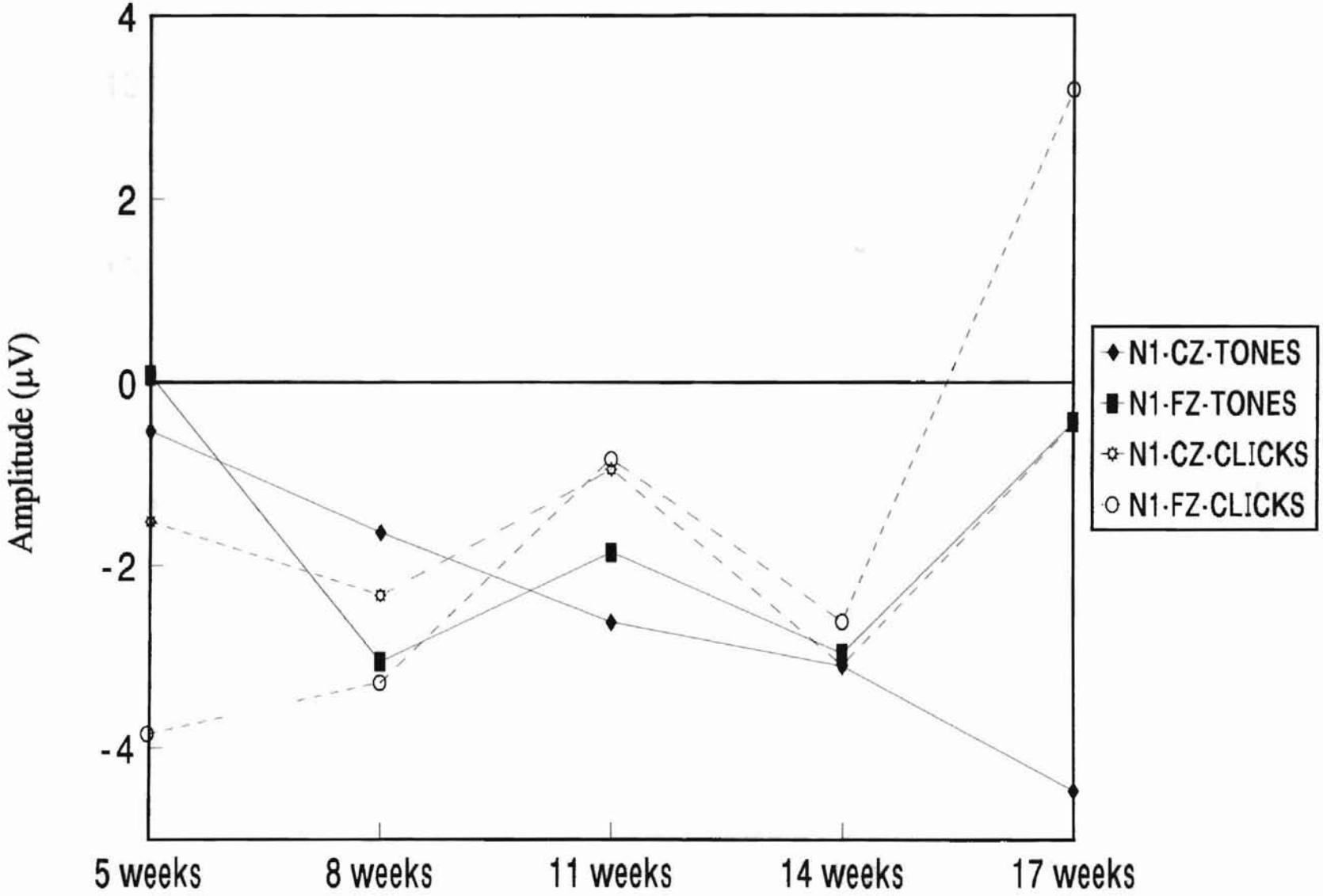
Figure 12. Mean peak latency for N1 for tones and clicks across ages at Cz and Fz.

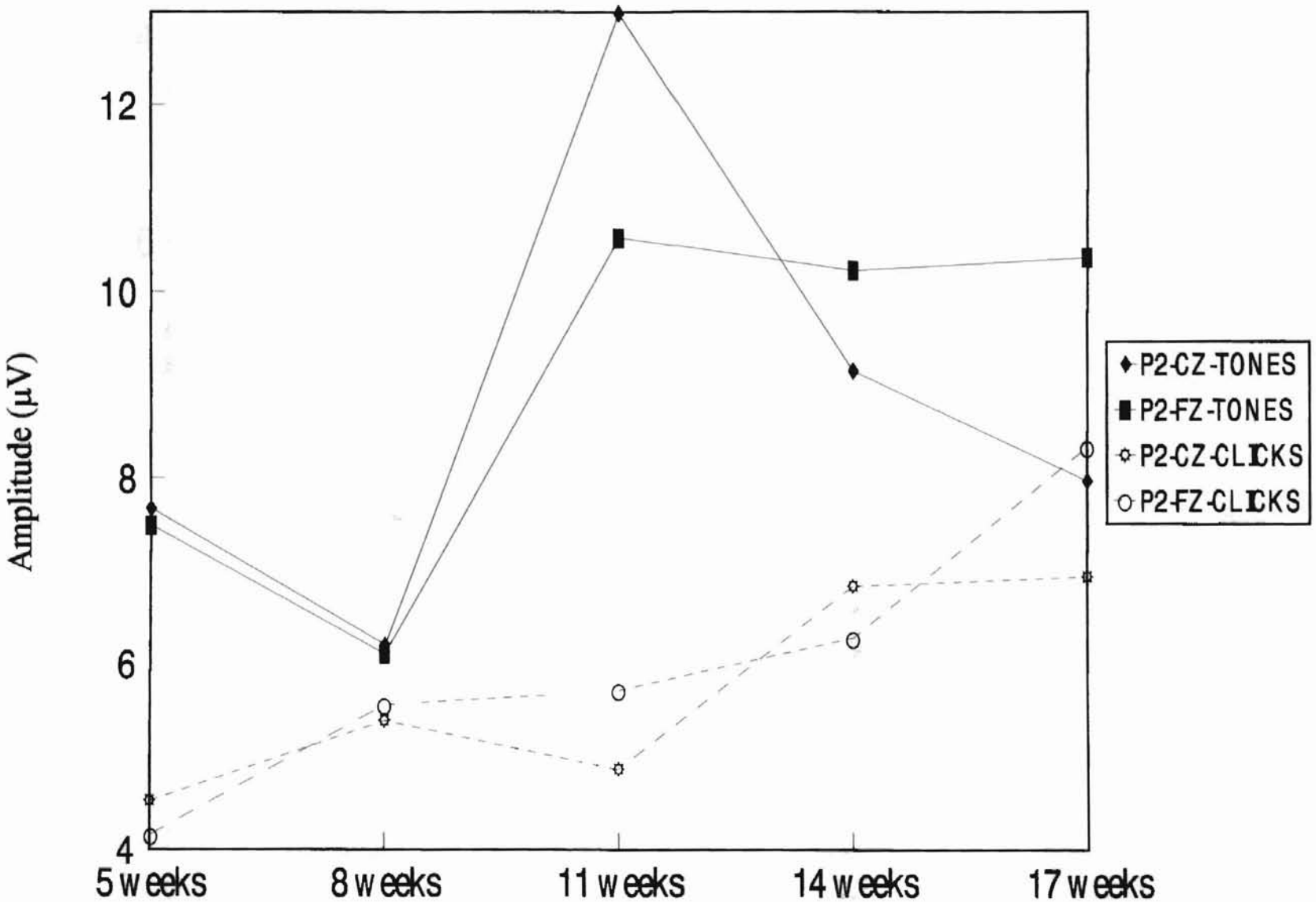
Figure 13. Mean peak latency for P2 for tones and clicks across ages at Cz and Fz.

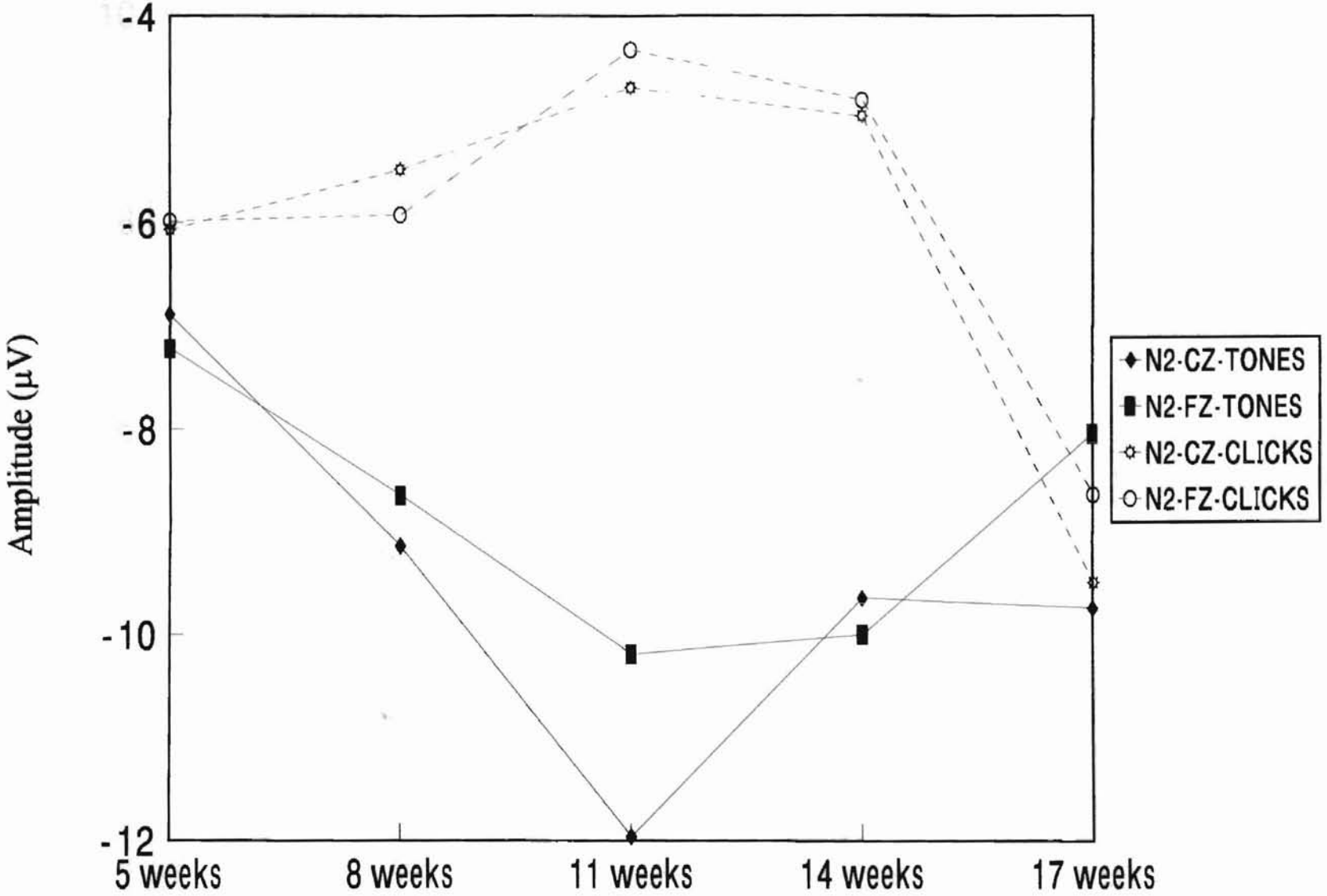
Figure 14. Mean peak latency for N2 for tones and clicks across ages at Cz and Fz.

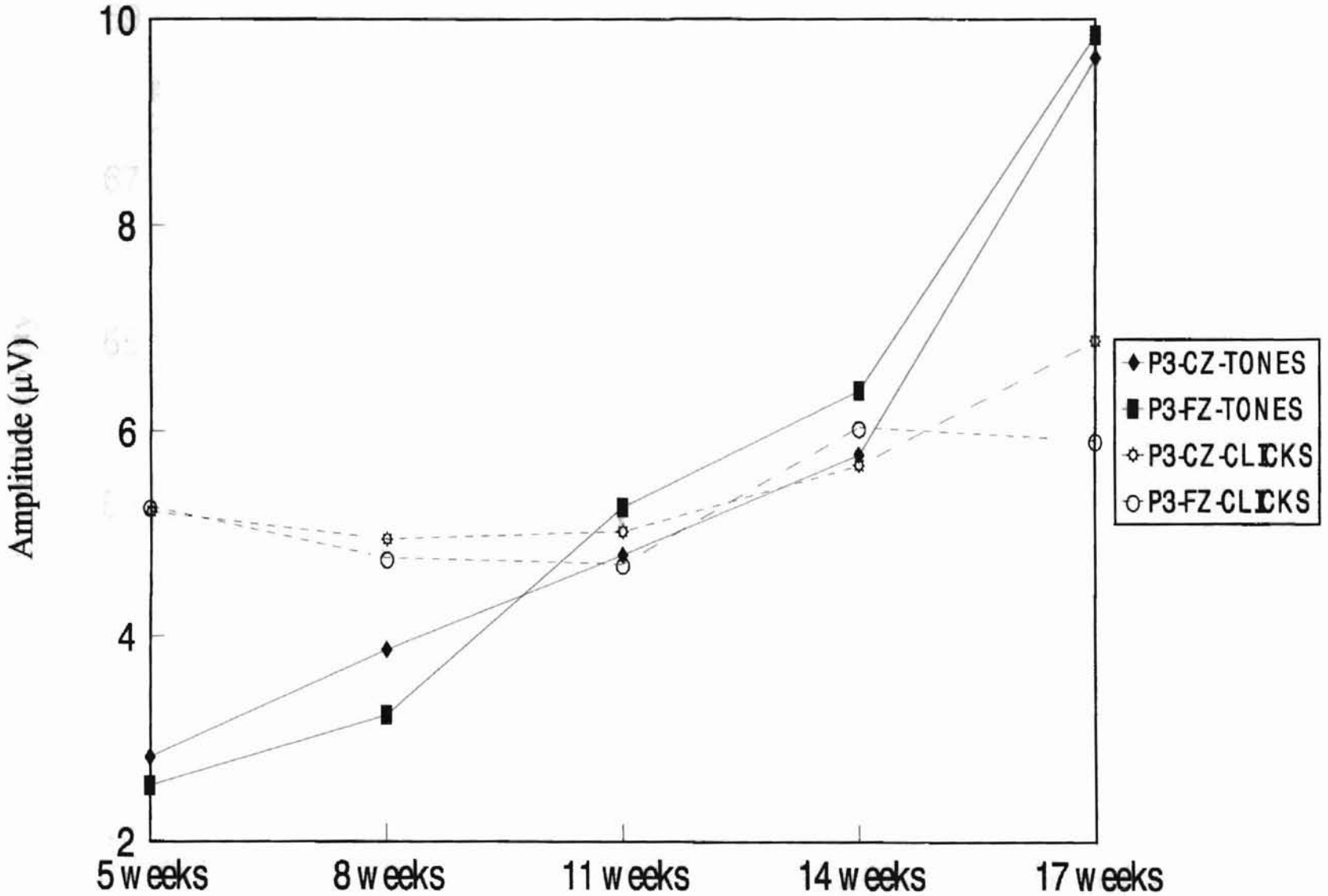
Figure 15. Mean peak latency for P3 for tones and clicks across ages at Cz and Fz.

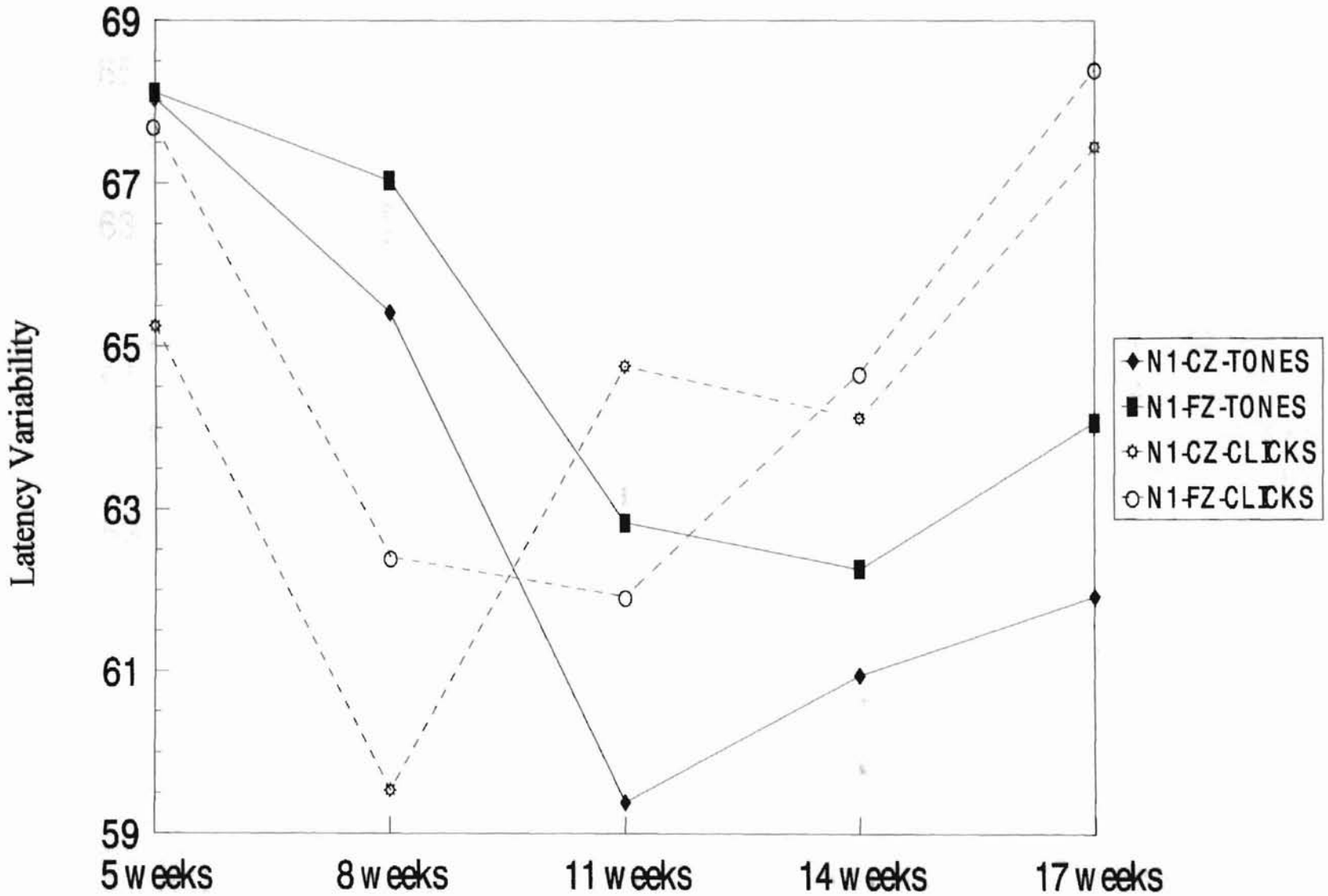
constant latency
variable latency
variable latency
average
1 2 3 4 5 6 7 8 9 10
time points

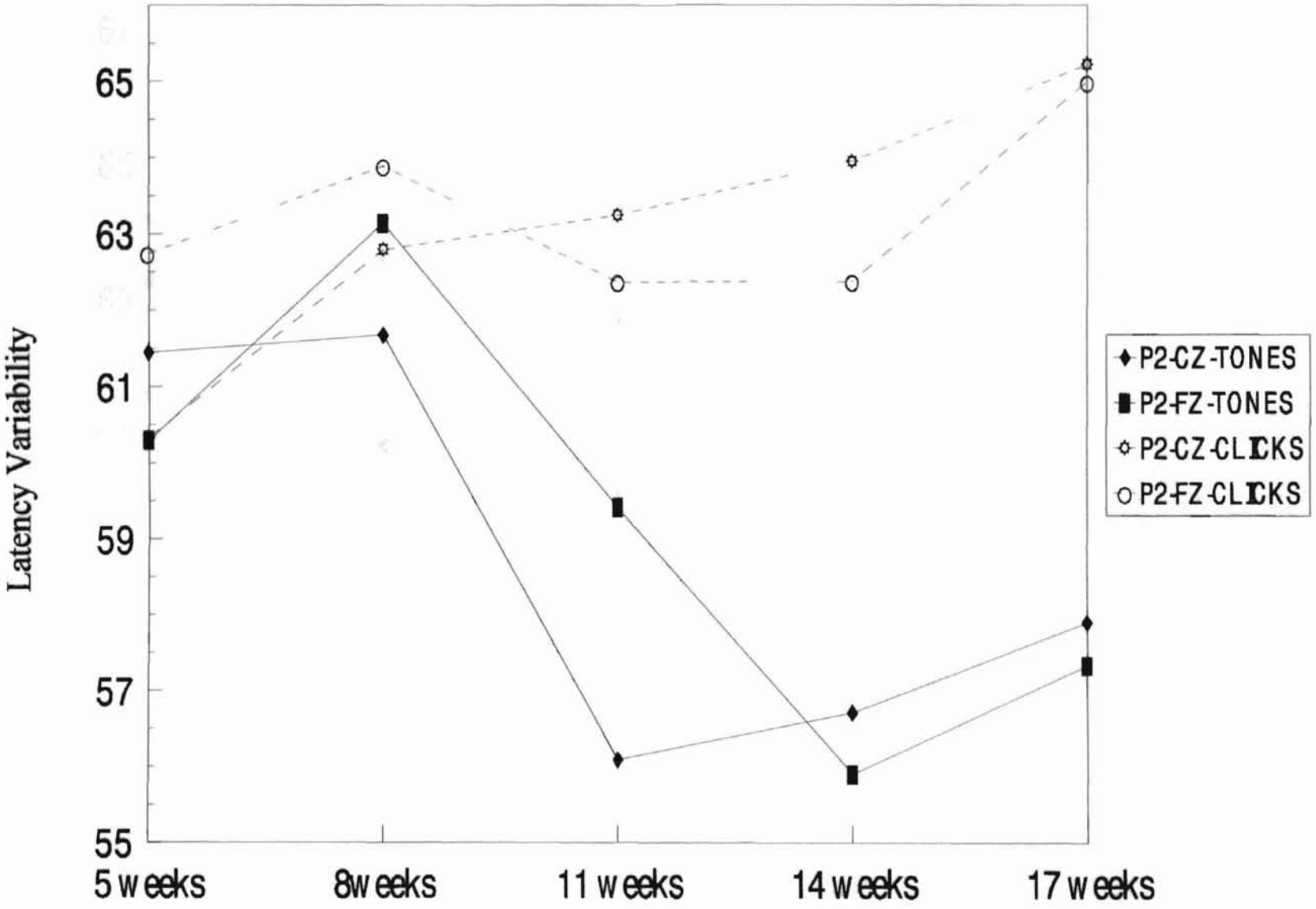

4
2
0
-2
-4
Amplitude (μV)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N1·CZ·TONES
N1·FZ·TONES
N1·CZ·CLICKS
N1·FZ·CLICKS

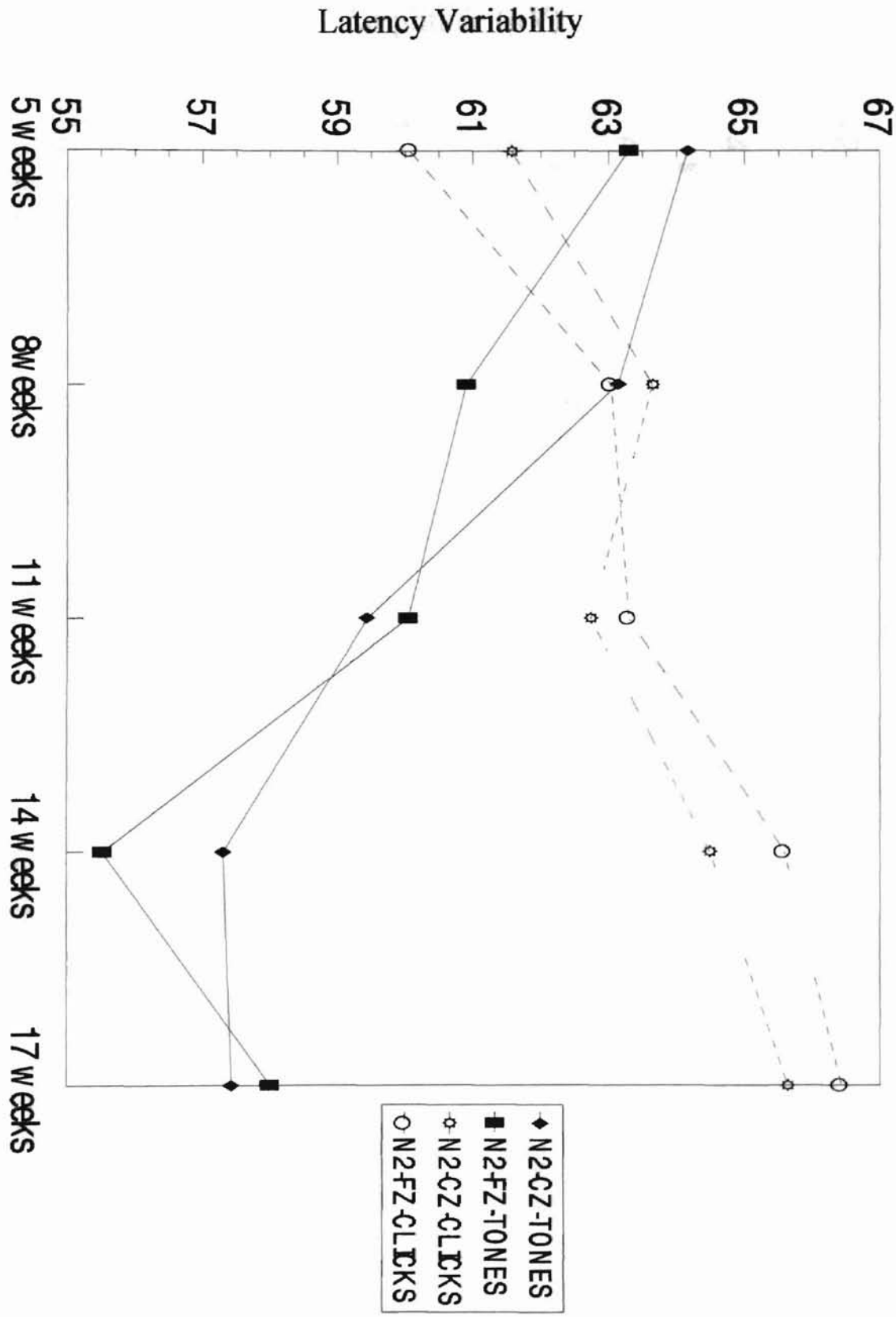

Amplitude (μV)
12
10
8
6
4
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P2-CZ-TONES
P2-FZ-TONES
P2-CZ-CLICKS
P2-FZ-CLICKS

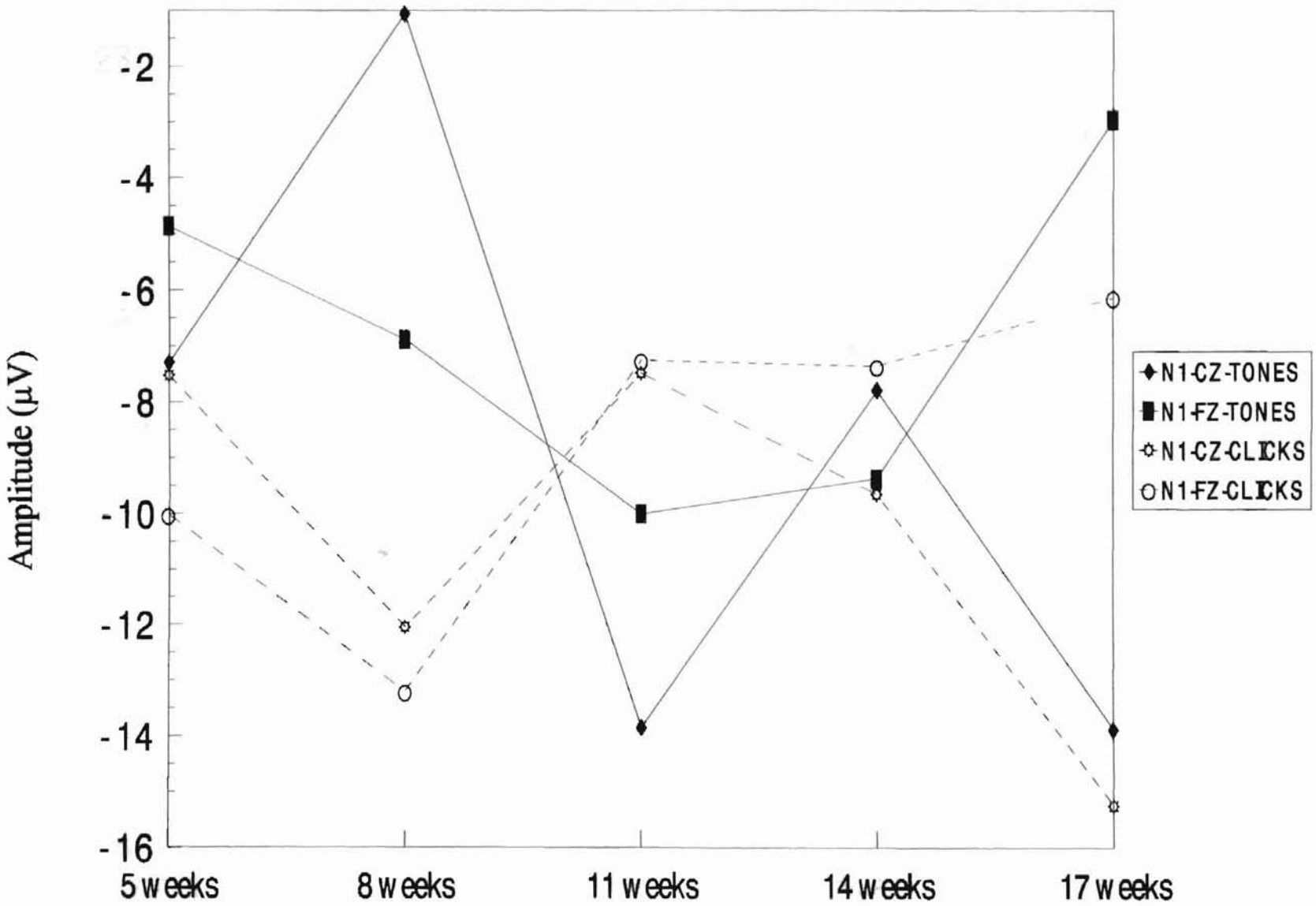

-4
-6
-8
-10
-12
Amplitude (μV)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N2-CZ-TONES
N2-FZ-TONES
N2-CZ-CLICKS
N2-FZ-CLICKS

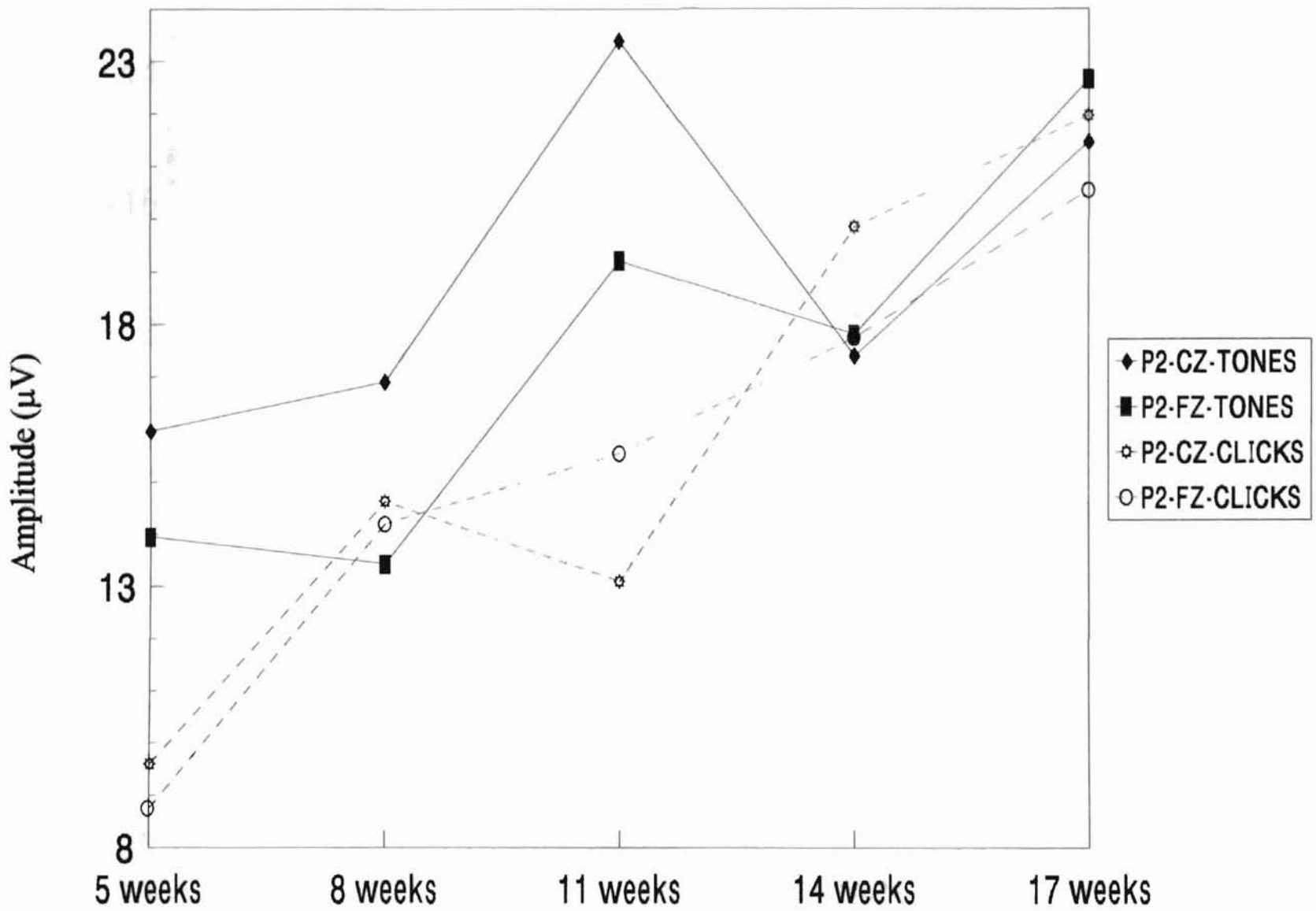

10
8
6
4
2
Amplitude (μV)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P3-CZ-TONES
P3-FZ-TONES
P3-CZ-CLICKS
P3-FZ-CLICKS

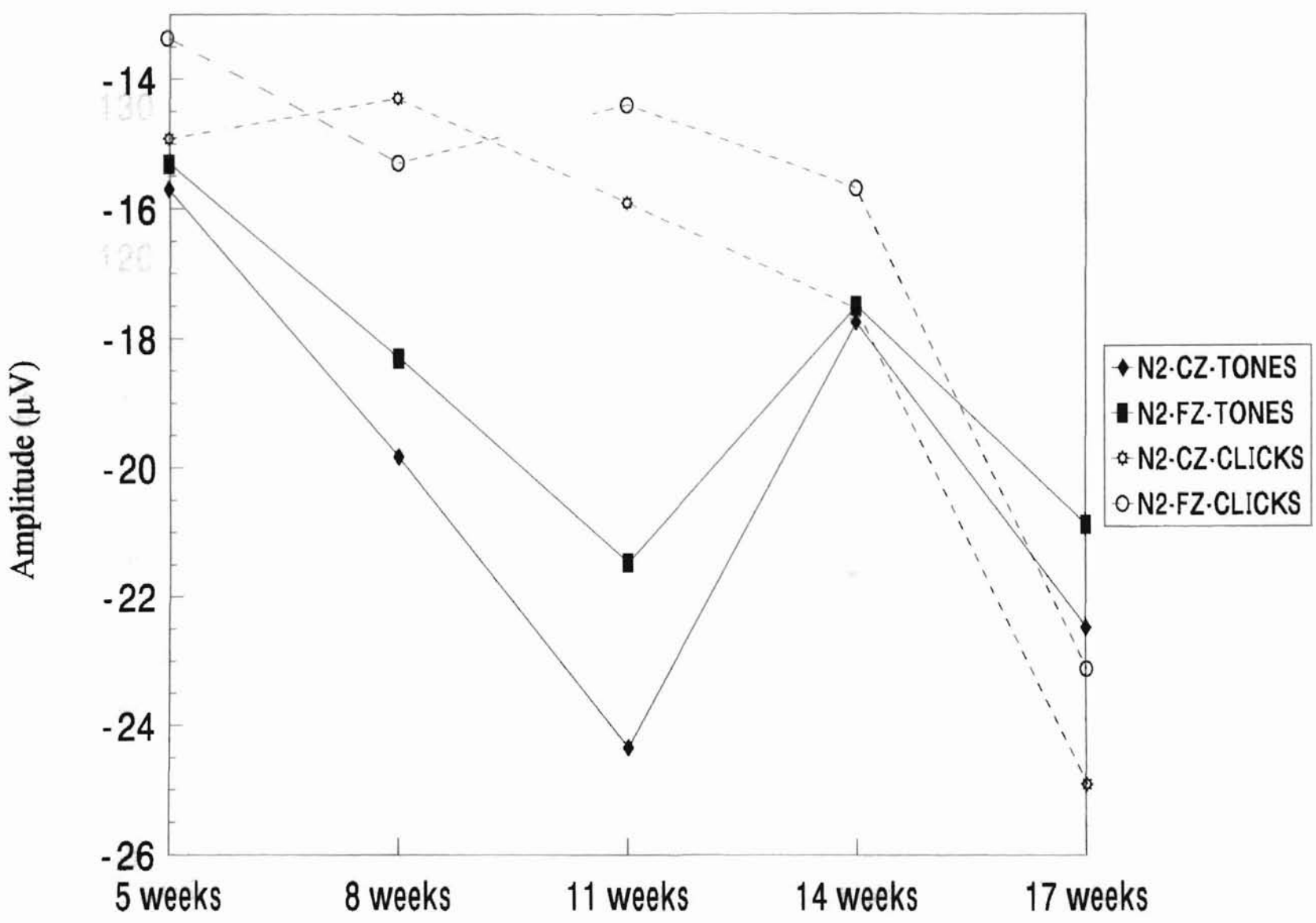

Latency Variability
69
67
65
63
61
59
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N1-CZ-TONES
N1-FZ-TONES
N1-CZ-CLICKS
N1-FZ-CLICKS

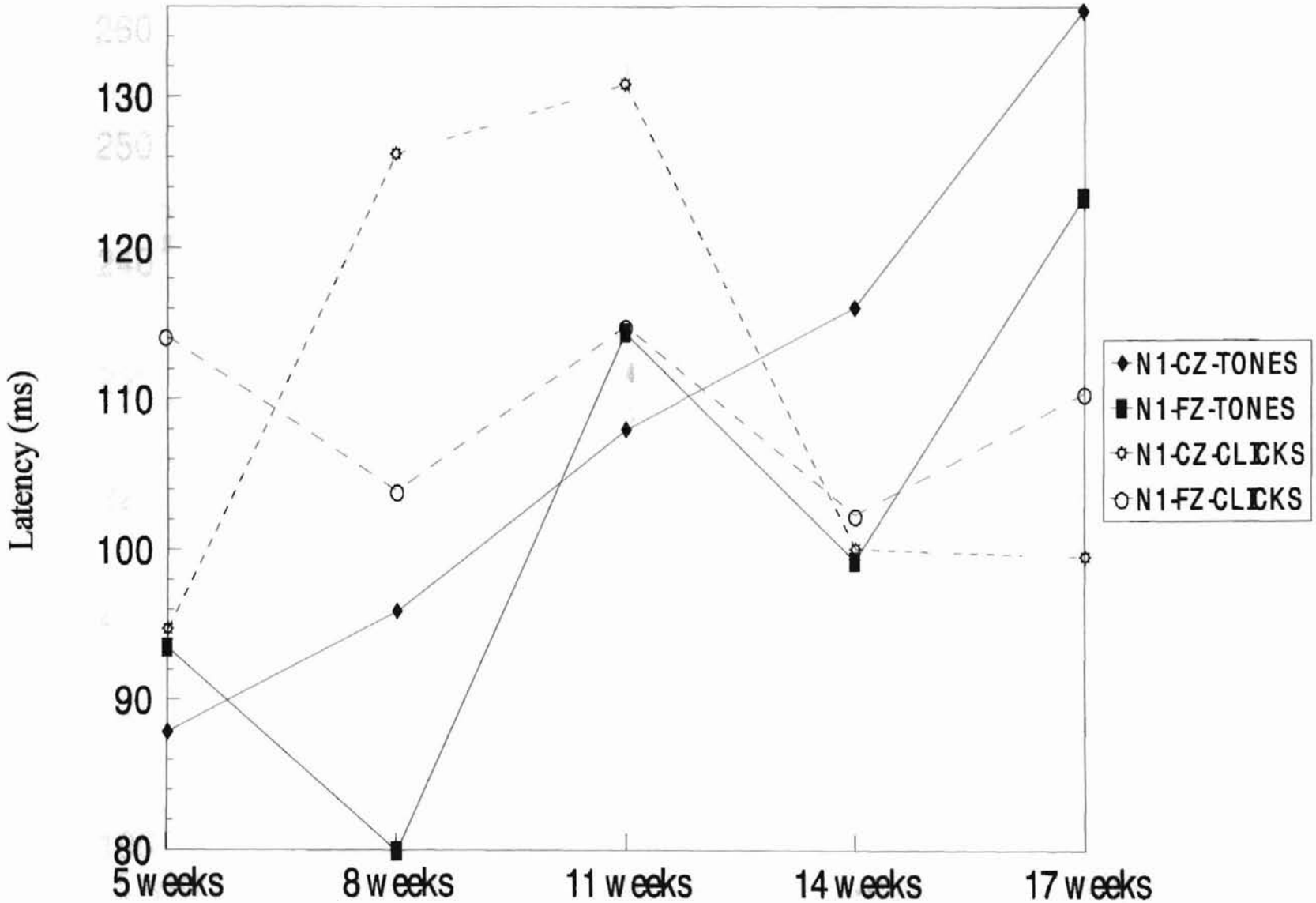

Latency Variability
65
63
61
59
57
55
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P2-CZ-TONES
P2-FZ-TONES
P2-CZ-CLICKS
P2-FZ-CLICKS

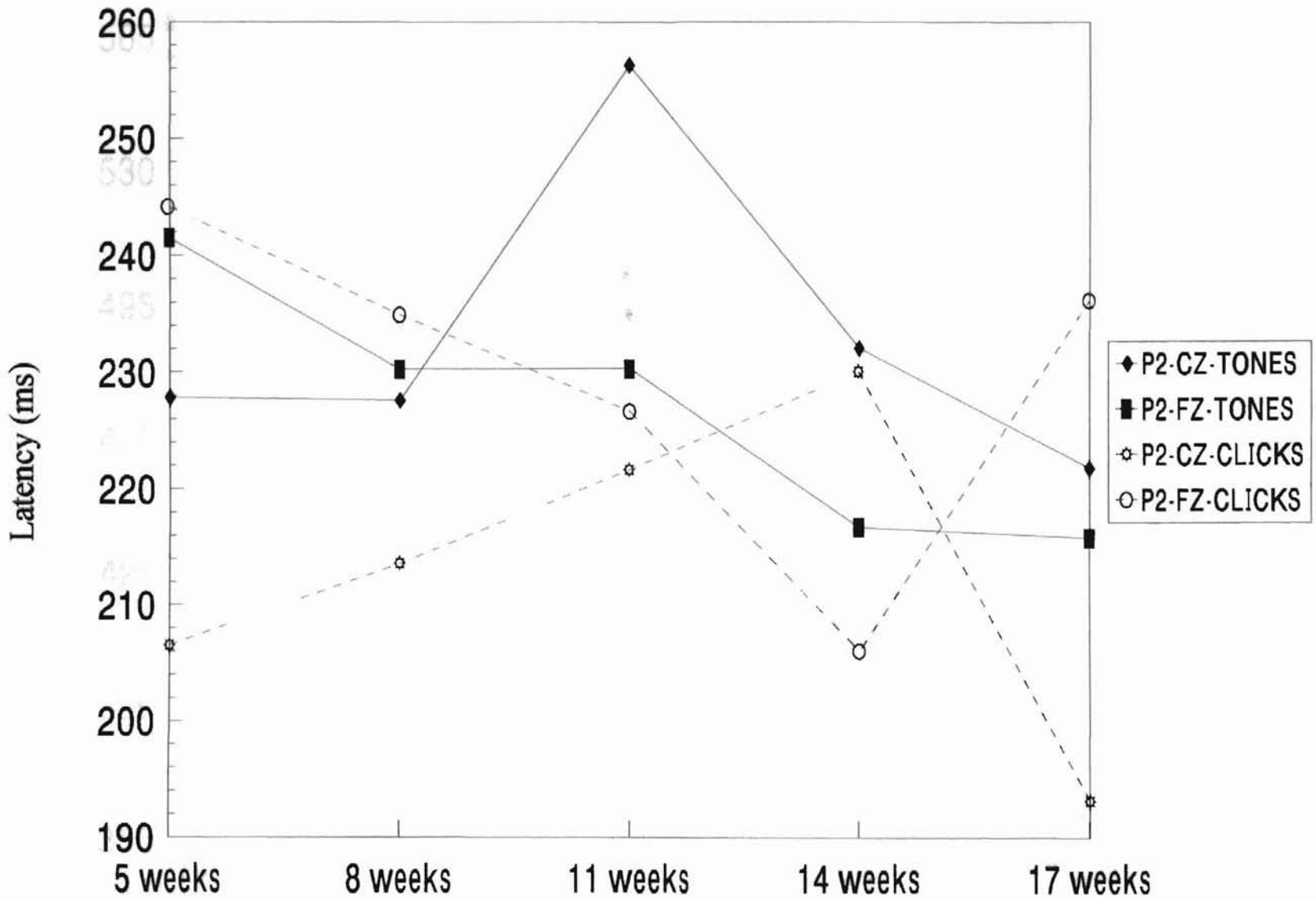

Latency Variability
67
65
63
61
59
57
55
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N2-CZ-TONES
N2-FZ-TONES
N2-CZ-CLICKS
N2-FZ-CLICKS

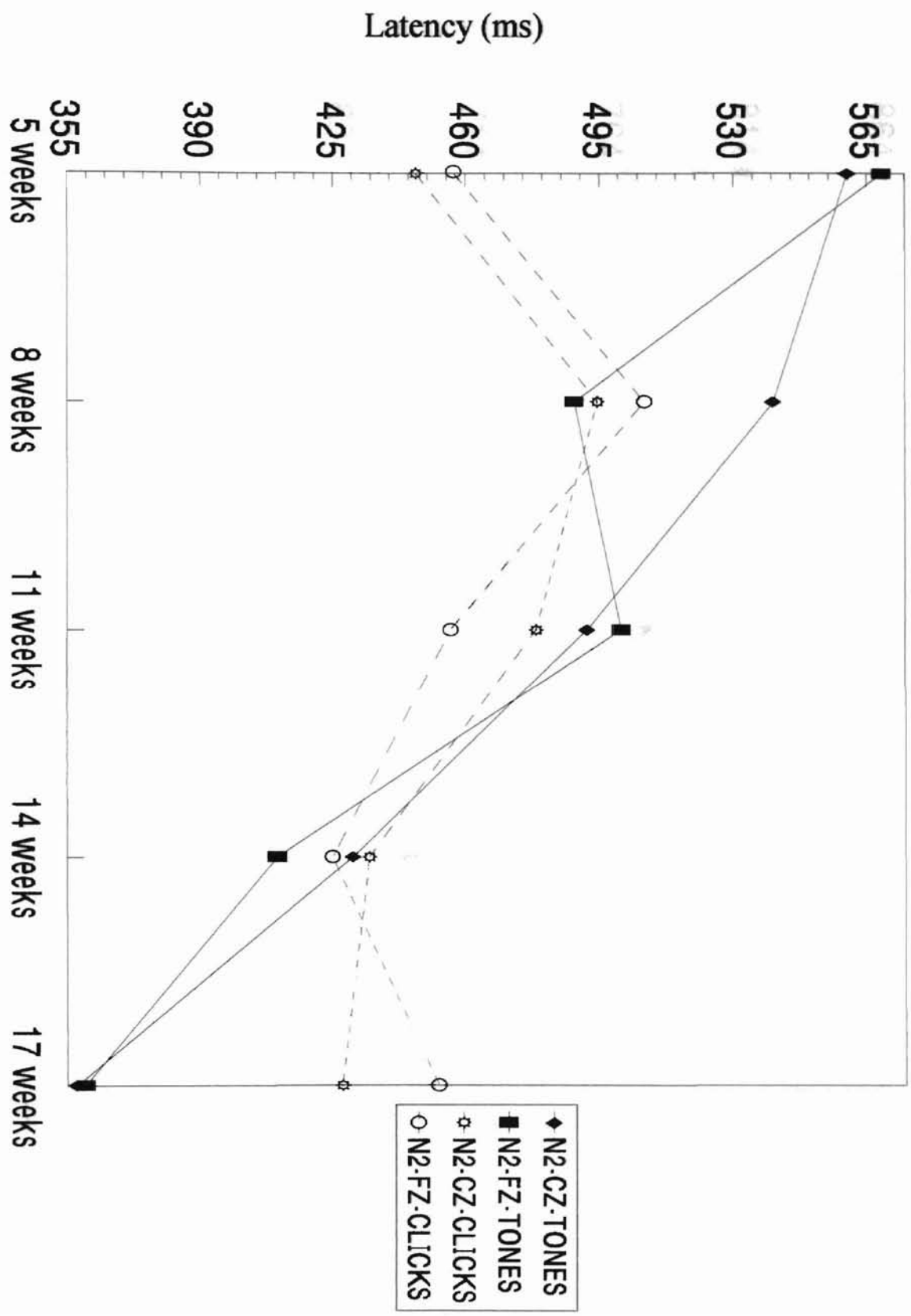

Amplitude (μV)
-2
-4
-6
-8
-10
-12
-14
-16
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N1-CZ-TONES
N1-FZ-TONES
N1-CZ-CLICKS
N1-FZ-CLICKS

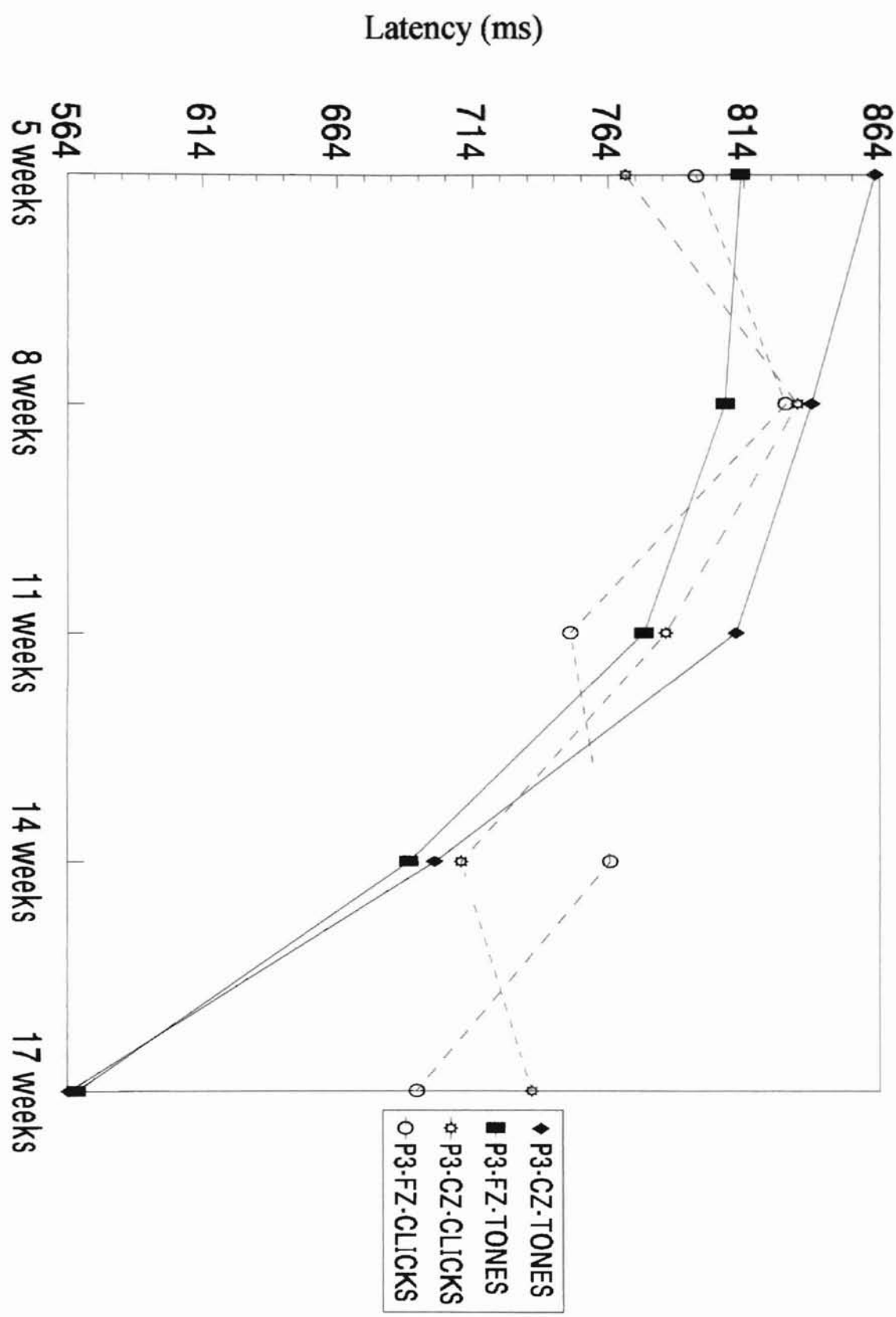

23
18
13
8
Amplitude (μV)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P2-CZ-TONES
P2-FZ-TONES
P2-CZ-CLICKS
P2-FZ-CLICKS


-14
-16
-18
-20
-22
-24
-26
Amplitude (μV)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N2·CZ·TONES
N2·FZ·TONES
N2·CZ·CLICKS
N2·FZ·CLICKS


Latency (ms)
130
120
110
100
90
80
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N1-CZ-TONES
N1-FZ-TONES
N1-CZ-CLICKS
N1-FZ-CLICKS


260
250
240
230
220
210
200
190
Latency (ms)
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P2-CZ-TONES
P2-FZ-TONES
P2-CZ-CLICKS
P2-FZ-CLICKS


Latency (ms)
355
390
425
460
495
530
565
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
N2-CZ-TONES
N2-FZ-TONES
N2-CZ-CLICKS
N2-FZ-CLICKS


Latency (ms)
564
614
664
714
764
814
864
5 weeks
8 weeks
11 weeks
14 weeks
17 weeks
P3-CZ-TONES
P3-FZ-TONES
P3-CZ-CLICKS
P3-FZ-CLICKS

Appendix

INSTITUTIONAL RESEARCH BOARD
FOR HUMAN SUBJECTS
OKLAHOMA STATE UNIVERSITY

Proposal Title: Evoked Potential VAriability as a Measure of Infant Development

Principle Investigator: David C. Thomas

Date: January 20, 1987

This application has been reviewed by the IRB and

Processed as; Exempt [ ] Expedite [ ] Full Board Review [x]

Renewal or Continuation [ ]

Approval Status: Approved [X] Please send me exact title and modified consent form.

Disapproved [ ]

Conditional [ ]

Deferred [ ]

Comments, Modifications/Conditions for Approval or Reason for Disapproval:

There is an inconsistency in the title between the proposal and the HS application.

Item 4 could be omitted from the consent form and the consent form should mention the purpose of the study. A time period for studying the infant should be added to the consent form.

Signature: Margaret J. Weber
Chair of University Board

Date: Jan. 20, 1987

VITA

Vickie M. Little

Candidate for the Degree of

Master of Science

Thesis: SINGLE-TRIAL ANALYSES OF DEVELOPMENTAL TRENDS IN INFANT AUDITORY EVENT-RELATED POTENTIALS

Major Field: Psychology

Biographical:

Education: Graduated from Kingfisher High School, Kingfisher, Oklahoma in May 1976; received Associate of Arts degree in Psychology from Redlands Community College, El Reno, Oklahoma in May 1989; received Bachelor of Arts degree in Psychology with a minor in Chemistry from the University of Central Oklahoma, Edmond, Oklahoma in December 1991. Completed the requirements for the Master of Science degree in Psychology at Oklahoma State University in December, 1996.

Experience: Served as undergraduate and graduate teaching assistant, Department of Psychology, University of Central Oklahoma, Edmond, Oklahoma, 1990 to 1994; employed by Redlands Community College as an instructor in the Behavioral Sciences Division, 1992 to 1994; employed by Oklahoma State University, Department of Psychology as a graduate research assistant; Oklahoma State University, Department of Psychology, 1994 to present.

Professional Memberships: Society for Neuroscience, Oklahoma Psychological Society, Southwestern Psychological Association.