Does the ACC Have Potential as an Index of Early Speech Discrimination Ability? A Preliminary Study in 4-Month-Old Infants With Normal Hearing

Susan A. Small¹ and Janet F. Werker²

Objective: The acoustic change complex (ACC), an auditory evoked potential (AEP) comprises overlapping slow cortical responses, which reflects discrimination capacity in the absence of attention, has not yet been recorded in infants. Because the ACC is a large response, it may be useful as an index of discrimination for infants at both the individual and group level. This is an advantage compared with mismatch negativity, another AEP that reflects discrimination of a change in stimulus, because mismatch negativity is based on difference waves and is most sensitive to group effects. The two objectives of this study were to determine whether: (1) the ACC can be elicited to a change in the English consonants /da/ and /ba/ in young infants and adults whose native language is English, and (2) the ACC can also be elicited to changes in Hindi consonant contrasts reflecting the predicted patterns of discrimination for young infants reported in previous studies.

Design: Participants were six adults and twenty-five 4-month-old infants whose native language was English, and were at low risk for hearing loss. Stimuli were concatenated consonant pairs comprised from a dental /da/, plus either /ba/, Hindi retroflex /Da/, a second /da/ or a silent period (i.e., /dada/, /daba/, /DaDa/ and /da_/). It was predicted that adults would show the largest ACC to /daba/, similar responses to /dada/ and /DaDa/ and no ACC to /da_/ whereas, it was predicted that infants would show a similar ACC to /daba/ and /DaDa/ a smaller ACC to /dada/ and no ACC to /da_/ The stimuli were a total of 564 msec in duration and were presented at 86 dB peak SPL with an interstimulus interval of 2200 msec. At least 100 accepted trials for each participant were required in the final waveform to be included in the study. Individual peak amplitudes and latencies were measured for the P1, N1, P2, and N2 components of the response to the initial /da/ and the ACC. Grand mean waveforms were averaged for each stimulus condition.

Results: ACCs were elicited in adults to /dada/, /daba/, and /DaDa/ with a trend toward a larger grand mean ACC for /daba/ compared with the other stimulus conditions. For infants, cortical responses to /da_/ resembled the adult P1–N1–P2 complex in morphology but had much longer latencies; /daba/ was the only stimulus that consistently elicited ACCs in infants. The ACC to /daba/ had a more distinct and less variable morphology compared with both /dada/ and /DaDa/, which might reflect that the infants detected a greater change from /dada/ to /ba/ than from /dada/ to either /da/ or /Da/. It may also be the case that the ACC could not be detected for these other stimuli because the stimulus duration and interstimulus intervals used in this study were not optimal for eliciting ACCs for a range of stimuli. The pattern of speech discrimination, as reflected by the ACC, only loosely parallels the behavioral discrimination patterns reported in previous studies.

Conclusions: These preliminary findings show that it is possible to record an ACC in young infants and provide a starting point for further investigation of the infant ACC and its utility as an index of discrimination.

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¹School of Audiology and Speech Sciences, The University of British Columbia, Vancouver, British Columbia, Canada; and ²Department of Psychology, University of British Columbia, Vancouver, British Columbia, Canada.

INTRODUCTION

The early speech-perception skills of infants, which lay the foundation for later language learning, have been extensively studied in infants with normal hearing but are not fully understood. Very little is known about how these skills develop in young infants with hearing loss. One of the challenges of investigating speech-discrimination ability in infants is that their responses, whether behavioral or physiological, change as they mature and typically differ from those of adults. Differences in responses to speech stimuli at the level of the auditory cortex likely reflect changes in neuroanatomy and maturation of neural processing efficiency through all levels of auditory processing, and are potentially influenced by age- and frequency-dependent changes in mechanical properties of the outer and middle ear where auditory input is first altered before it reaches the cochlea. Another significant issue inherent to infant studies is that testing time is usually very limited compared with that of adults, which restricts the tools that we can use to accurately assess the processing of auditory stimuli. As a consequence, both the collection and interpretation of infant data in response to speech stimuli for infants that differ in age and hearing sensitivity are very challenging.

Much of the infant speech-perception research has involved behavioral tasks (e.g., review by Werker & Tees 2005). However, physiological measures such as cortical event-related potentials (ERPs) tend to be more sensitive to the effects of learning or training than behavioral tasks (Tremblay et al. 1998, 2001; Tremblay & Kraus 2002), and are commonly used to investigate the neural processes that underlie discrimination of simple and complex auditory stimuli. The slow cortical response (P1–N1–P2), which was first discovered in 1939 by Davis is an obligatory response that reflects the neural encoding of the onset of an auditory stimulus. It is well established that there are multiple anatomical structures that contribute to each of the components in this response and that the morphology, topography and amplitude and latency characteristics of these components are differentially affected by maturation, age, and stimulus variables (reviews by Näätänen & Picton 1987; Crowley & Colrain 2004; Wunderlich & Cone-Wesson 2006).

There are a number of studies that have investigated the effects of age on the obligatory P1–N1–P2 response spanning from infancy to the senior years. On the basis of the findings of these studies, it is well documented that: (1) maturation of the human auditory system does not occur at the same rate throughout the auditory system, (2) there are parallel subsystems in the thalamocortical pathway based on differential effects of maturation on latencies of individual peaks, and (3) different maturation rates have helped isolate the generators that contribute to the components of this response in adults (Ponton et al. 1996a, 1996b).
For the mature cortical response, the primary auditory cortex in Heschl’s gyrus is the major contributor to P1 (Wood & Wolpaw 1982; Reite et al. 1988; Liégeois-Chauvel et al. 1994; Huotilainen et al. 1998); however, the hippocampus, planum temporale, and lateral temporal cortex may also be contributors (Liégeois-Chauvel et al. 1994, 1999; Howard et al. 2000). In a detailed review, Näätänen and Picton (1987) described at least three anatomically and functionally distinct obligatory components that comprise the N1. The first component of N1 is a negative wave generated by vertical dipoles in the auditory cortex in the superior portion of the temporal lobe. It is thought that the function of the neurons that elicit this component are threefold: (1) to alert the system that a stimulus is available for processing, (2) to read out sensory information from the auditory cortex, and (3) to establish a sensory memory trace in the auditory cortex (Näätänen & Picton 1987). The second component, the “T-complex,” which is biphasic with a positive peak at 100 msec and a negative trough at 150 msec (Wolpaw & Penry 1975), is known to be generated by a radial source in the secondary auditory cortex within the superior temporal gyrus but its functional significance is not well described (Näätänen & Picton 1987). The third component, a negative wave at 100 msec, is speculated to be generated outside the temporal cortex, perhaps in the thalamoreticular system, and may reflect an overall arousal of the neural networks, which facilitates processing efficiency. The P2 component is distinct from N1 and arises from multiple sources including the primary and secondary cortices, and the mesencephalic reticular activating system (reviewed by Crowley & Colrain 2004). The N2 component is prominent only in the immature slow cortical response and is best elicited by frontal electrodes (Sussman et al. 2008).

The slow cortical response can be recorded reliably in most infants and all adults; however, there are significant infant–adult differences in the morphology of the response and the amplitude and latency characteristics of the major components related to age and stimulus rate. The dominant components for adults are N1 and P2, which have latencies in the range of approximately 90 to 180 msec (Davis 1939). Infants are most often reported to have a biphasic or “P–N complex” (i.e., a large positive peak at approximately 120–250 msec, which could be single or double followed by a large negative peak at 250–400 msec), rather than the prominent N1 and P2 components and the smaller P1 elicited in adults (reviewed by Wunderlich & Cone-Wessøn 2006). However, it is possible to elicit a more complex waveform in infants and children with more similarities to the mature cortical P1–N1–P2 by increasing the duration and complexity of the stimulus and reducing the stimulation rate (Oehrich & Barnett 1972; Kurtzberg et al. 1984; Rotteveel et al. 1987; Shucard et al. 1987; Čepioniénë et al. 1998; Little et al. 1999; Gilley et al. 2005; Wunderlich et al. 2006). A prominent N2 component is more typical of an immature cortical response than a mature cortical response. For the purposes of this study, we will refer to the components of the slow cortical response as P1, N1, P2, and N2 for both adults and infants, although we do not expect N2 to be present in all cases.

The mismatch negativity (MMN) response, also a cortical response, reflects a preattentive detection of stimulus change and occurs at approximately 100 to 250 msec and can be used to assess discrimination of changes in acoustic and linguistic features in speech stimuli. MMN is calculated by subtracting the response to frequent standard stimuli (i.e., a sensory memory trace of the standard) from infrequent deviant stimuli and is believed to originate in the auditory cortex and possibly frontal cortices (reviewed by Näätänen 1992). First described in infants by Cheour-Luhtanen et al. (1995), the MMN has proven to be useful for revealing group differences in discrimination ability, for example, as a function of age or language experience (Dehaene-Lambertz & Bailleit 1998; Pang, et al. 1998; Rivera-Gaxiola et al. 2005). Nonetheless, the MMN has recognized limitations. It is not present in every infant and, when present, shows some variability in morphology (e.g., positivity instead of negativity in the difference wave) depending on the stimuli used to elicit the response and the age of the infant (Kushnirenko, et al. 2002; Morr et al. 2002; Trainor et al. 2003; Tsao et al. 2004; Friederici et al. 2007). A substantial drawback of the MMN for all ages is that it is primarily sensitive to group differences because of high variability in individual responses.

When the P1–N1–P2–N2 complex is elicited by acoustic changes in speech stimuli; the resultant waveform, the acoustic change complex (ACC), contains multiple overlapping P1–N1–P2–N2 complexes; discrimination of a change is reflected in the presence and characteristics of the response to the second stimulus (Martin & Boothroyd 1999). The ACC is similar to the MMN in that it reflects discrimination capacity in the absence of attention; however, it is much larger in amplitude and requires many fewer stimulus presentations because the ACC is not derived from a difference wave and every accepted stimulus trial contributes to the average. The ACC has not yet been recorded in infants but may yield a more robust and consistent response than MMN. Moreover, the ACC in adults is sufficiently robust to provide individual-level assessment, rather than only summary group data. Thus it has the potential to be useful for providing individual-level data for infants as well.

One area of great interest in understanding the normal developmental processes of language learning is the effect that typical linguistic experience has on the plasticity of the developing brain. Findings from behavioral and cortical ERP studies in infants with normal hearing support that there is a sensitive period in early infancy during which there is a switch from language-universal to language-specific perceptual categories after a period of exposure to the infant’s native language. Werker and Tae (1984) and Werker and Lalonde (1988) showed using a conditioned head-turn procedure that infants whose native language was English were able to discriminate Hindi consonant contrasts (dental /da/ and retroflex /Da/) behaviorally when they were less than 6 months of age but not at 10 to 12 months of age. Subsequent studies investigated this phenomenon in infants using MMN to better understand the neural mechanisms that underlie this change in discrimination ability. For example, Cheour et al. (1998) showed that MMN could be elicited to non-native Finnish vowel contrasts in 6-month-old infants but the responses were greatly attenuated in 12-month-old infants. Rivera-Gaxiola et al. (2005) reported similar findings for 7- and 11-month-old American infants in response to English and Spanish consonant contrasts. This phenomenon of change from language-universal to language-specific speech categories in the first year of life is an ideal model for investigating the utility of the ACC as an index of discrimination ability in young infants.
in the English consonants /da/ and /ba/ in young infants whose native language is English and who have normal hearing. The second objective of this study, assuming that it was feasible to elicit an ACC in infants, was to determine whether the ACCs recorded in these young infants reflect the pattern of discrimination for Hindi consonant contrasts (dental /da/ and retroflex /Da/) that has been shown previously to characterize the switch from language-universal to language-specific discrimination skills. The /da/ and /ba/ tokens are clearly different phonemes for both English and Hindi speakers at all ages; /da/ and /Da/ should be discriminated as different phonemes by very young infants whose native language is English because their experience with their native language is limited. The predicted pattern is that these young infants will have a larger ACC for a change from /da/ to either /ba/ or /Da/ than from /da/ to /da/ (i.e., no change). These infant findings will also be compared with recordings to the same stimuli for an adult control group to investigate infant–adult differences in the ACC. Given that adults whose first language is English have difficulty discriminating the non-native /da_/–/Da/_ contrast behaviorally (Werker et al. 1981; Werker & Tees 1984), it is predicted that the adults will show a larger ACC for a change from /da/ to /ba/ than to either /da/ to /da/ or /da/ to /Da/.

**MATERIALS AND METHODS**

**Participants**

Participants included a group of six adults (mean age: 27.6 years) and a total of 31 infants (mean age: 20.1 weeks; range: 16.0–28.4 weeks), all with normal hearing. Adult participants were recruited from the community to form a control group and were considered to have normal hearing if thresholds were 25 dB HL or lower for 500, 1000, 2000, and 4000 Hz. The infant participants were recruited from a subject database of the Infant Studies Centre at the University of British Columbia. By parent report, all infants were healthy with no history of either middle ear involvement or neurological problems. The infants were screened for hearing using transient-evoked otoacoustic emissions using the Madsen AccuScreen Pro (GN Otometrics). Infants who passed the transient-evoked otoacoustic emissions screening test in both ears were considered to be hearing normal and thus included in the study. Five infant participants were excluded because data collection was not completed for any of the attempted stimulus conditions because of excessive movement, vocalizations or crying.

**Stimuli**

Dental /da/, Hindi retroflex /Da/, and /ba/ were paired to create stimuli that contained an acoustic change from /da/ to /Da/ and from /da/ to /ba/ (i.e., /daba/ and /daDa/). These stimuli were chosen to investigate the acoustic change from the first /a/ to the second consonant, /D/ or /b/, in the presence of the initial /d/. We also elicited responses to /da/ followed by silence (i.e., /da_/) during which a single response, P1–N1–P2–N2 or P–N complex, to the onset of /da/ is predicted (and possibly a small response to the offset of the stimulus). The pairing, /daba/, was also used to elicit an ACC to serve as a control stimulus for no change in adjacent consonant pairs.

The stimuli were made by concatenating two synthetic Hindi speech tokens (denoted as S1 and S2) that were selected from a synthesized 16-step continuum modelled on stimuli used in a previous study (Werker & Lalonde 1988). The three speech tokens used in the present study were /ba/, /da/, and /Da/ which are equivalent to the 3rd, 8th, and 13th tokens, respectively, presented in the study by Werker and Lalonde (1988). The stimuli comprised a five-formant (F) structure. The steps in the continuum were created by varying the starting frequency of F2 and F3. The fundamental frequency was 100 Hz for the first 100 msec then rose to 120 Hz during the remaining 182 msec. F1 began at 250 and increased to 500 Hz over a period of 50 msec and F4 and F5 were constant at 3500 and 4000 Hz, respectively. The duration of the transitions for both F2 and F3 was 50 msec, and their steady-state frequencies were 1090 and 2440 Hz, respectively. The starting frequencies for F2 for /ba/, /da/ and /Da/ were 1000, 1250, and 1500 Hz, respectively. The starting frequencies for F3 for /ba/, /da/, and /Da/ were 2384, 2528, and 2627 Hz, respectively. The only additional difference between /ba/ and the other tokens was that the frequency of the burst was lower so that the burst was perceived as part of the syllable, /ba/; this modification was only required up to and including the third token, after which the burst frequency was held constant. The speech tokens from Werker and Lalonde were saved as .wav files and modified using the sound program in Neurobiomedics STIM2 software. A portion of the vowel segment of the speech token was removed to achieve the desired stimulus duration. Each of the speech tokens was 282 msec in duration. Each stimulus was made up of two speech tokens, S1 and S2, so that the total duration of S1S2 was 564 msec. Cortical ERPs were recorded using three S1S2 stimuli (/dada/, /daba/, and /daDa/). Recordings were also made to (/da_/), which was equivalent to S1 plus a silent period with a total duration of 564 msec. The stimuli were presented with an interstimulus interval (ISI) of 2200 msec. These four stimulus conditions were presented at 86 dB peak SPL in blocks of at least 200 with the goal of obtaining an average of at least 100 trials for each participant in the final waveform. For infants, it was expected that the number of recorded trials would need to be adjusted online depending on the state of the infant; therefore, the recording of additional trials was permissible at the discretion of the examiner. Recordings were also made to /ba_/ and /Da_/ for the adult participants to determine whether the cortical responses to /da_/ and /Da_/ differ in their amplitude and latency characteristics.

The stimulus generated by STIM2 was then delivered to Tucker Davis Technologies PA5 and SM5 modules where 10 dB of gain was added before routing the stimulus to the HB7 headphone driver. The stimulus was then delivered to a loudspeaker in the sound booth, which was placed so that it was centered 1 m in front of the infant who was held by a parent seated in a comfortable chair, both facing toward the loudspeaker.

**Calibration**

The speech stimuli were calibrated in the sound field using a Larson Davis System S24 and Larsen Davis Model 2559 0.5 in random-incidence microphone placed at the approximate position of the infant’s head. The stimulus level was calibrated in dB peak SPL.
ERP Recording

The ERPs were recorded using a four-channel electrode montage, including one pair of bipolar electrodes for monitoring vertical eye movements. Individual gold-plated electrodes were placed on lightly abraded skin at Cz, C3, M1, and M2, and FPZ (International 10–20 system). C3 was selected in addition to Cz because language processing is lateralized to the left hemisphere. (Only the waveforms recorded at C3 are presented as the responses at Cz were very similar.) Electrodes were also pasted above and below the center of the left eye on the low forehead and cheek, respectively. The electrode placed at the low forehead acted as ground and M2 served as the reference electrode. The electroencephalograph (EEG) was recorded using the Compumedics Neuroscan Synamps2 and SCAN 4.3 software. All inter-electrode impedances were below 5 kΩs using the SCAN 4.3 impedance routine.

The EEG channels were amplified (gain setting = 500) and filtered using a 30 Hz low-pass filter and a 1.0 Hz high-pass filter. The EEG was then processed using a 1000 Hz analog-to-digital conversion rate. Each EEG epoch was recorded over a latency window of −100 to 1400 msec and was made up of 1501 data points. Single-trial ERP waveforms were baseline corrected across the entire sweep duration, then corrected for ocular artifact. The EEG was corrected for ocular artifacts using an average of three epochs, which contained ocular movement greater than 250 μsec. Epochs over −100 to 300 μsec. Artifact rejection was conducted manually on single-trial ERPs by visual inspection to eliminate epochs of electrophysiologic activity that exceeded 75 μV in amplitude over a range of −100 to approximately 800 μsec. Manual artifact rejection was selected to optimize the number of accepted epochs in each average ERP waveform. The ERPs to the S1S2 and S1 plus silence stimuli were averaged separately and a final baseline correction was performed on the averaged trials.

Each individual waveform was based on the total number of epochs recorded (varied with each infant) minus the number of rejected epochs. A minimum of 200 epochs was recorded for each condition to ensure that an adequate number of epochs would be included in the final waveform after noisy epochs were rejected. Because this was difficult to estimate with certainty during online recordings, the total number of recorded epochs varied from 216 to 552 across stimulus conditions depending on the amount of movement or vocalization exhibited by the participant as shown in Table 1 for adults and Table 2 for infants.

A minimum of 100 accepted epochs per stimulus condition was required to include the data in the study for both age groups. The actual number of accepted epochs ranged from 102 to 335 across stimulus conditions and participants (Tables 1 and 2). Despite the variability in epochs recorded and accepted for each stimulus condition, the mean number, standard deviation, and range of accepted epochs were similar across stimulus conditions within each age group.

Procedure

Testing was conducted in a double-walled sound-attenuated booth in the Human Auditory Physiology Laboratory at the University of British Columbia. The average ambient noise levels in the sound-attenuated booth for 1-octave bands centered at 500, 1000, 2000, and 4000 Hz were 12, 10, 10, and 12 dB SPL, respectively. Adults sat in a comfortable chair and watched a movie with subtitles and no sound to assist in maintaining alertness throughout testing. Infant participants were only tested when quiet and alert while being held by a parent who sat in a comfortable chair facing the loudspeaker. An age-appropriate movie without sound was played on a flat-screen monitor directly behind the loudspeaker throughout the test session. This visual distractor was used to direct the infant’s attention toward the source of the stimuli, both to limit the changes in stimulus intensity that result from head movement and to reduce myogenic noise in the EEG. An assistant was also available to step into the sound booth to help engage the infant’s attention using puppets, quiet toys, or books as needed.

Cortical ERPs were elicited to as many stimulus conditions as possible for each participant. Infants were required to complete at least one stimulus condition to be included in the study. When one condition was completed, a second or third condition was attempted only if the infant remained content to sit on the parent’s lap. Testing was stopped if the infant was either upset or vocalizing continuously during the presentation of the stimuli. None of the infants completed all stimulus conditions and only seven completed more than one stimulus condition. In contrast, all adult participants completed all stimulus conditions. The stimulus conditions were selected in a randomized order. Hearing screening was performed in both ears at the end of the test session to establish that the participants were unlikely to have hearing loss.

For adults, the duration of recording and hearing screening time was approximately 2 hr. The total recording time ranged

<table>
<thead>
<tr>
<th>Stimulus Condition</th>
<th>/da_/</th>
<th>/dada/</th>
<th>/daba/</th>
<th>/daDa/</th>
<th>/ba_/</th>
<th>/Da_/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total epochs recorded Mean</td>
<td>308</td>
<td>300</td>
<td>305</td>
<td>302</td>
<td>295</td>
<td>305</td>
</tr>
<tr>
<td>1 SD</td>
<td>19</td>
<td>5</td>
<td>8</td>
<td>3</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Final epochs accepted Mean</td>
<td>194</td>
<td>164</td>
<td>193</td>
<td>179</td>
<td>170</td>
<td>172</td>
</tr>
<tr>
<td>1 SD</td>
<td>31</td>
<td>40</td>
<td>50</td>
<td>36</td>
<td>45</td>
<td>34</td>
</tr>
<tr>
<td>Artifact rejection rate</td>
<td>37%</td>
<td>45%</td>
<td>37%</td>
<td>41%</td>
<td>42%</td>
<td>44%</td>
</tr>
</tbody>
</table>

*The number of accepted epochs was measured after baseline adjustments, ocular corrections, and manual artifact rejections were conducted.*
from approximately 12 to 45 min for infants, including the time to obtain screening test results. Procedures for this study were approved by the University of British Columbia Behavioural Research Ethics Board. The adult participants signed a consent form before commencing the test session and received an honorarium. The parents of the infant participants signed a consent form before commencing the test session; all parents were paid a small honorarium and received a gift for their child at the end of each session.

Data Analyses

The morphologies of the ERP waveforms to /daba/ and /daDa/ were compared qualitatively with /da_/ and to /dada/ for responses recorded at C3 for each participant. The latency values for the components of the responses to S1 and S2 were measured from the onset of S1 and the onset of S2, respectively (latencies reported do not account for the propagation delay between the loudspeaker and the participant’s ear). The across-subject latency distributions for each ERP peak elicited to the S1 and S2 portion of the S1S2 stimulus were determined for each stimulus condition by means of visual inspection of a single waveform. The largest peaks within each of these latency windows were manually selected for each stimulus condition and described in terms of mean amplitude and latency. For S1 responses, individual amplitudes were measured from baseline-to-peak and individual latencies were measured at the peak amplitude. For S2 responses, the baseline was not always at 0 μV; in these cases, the new “baseline” was established as the point in the waveform at which the S2 P1 or N1 (if P1 absent) began its deflection. All baseline-to-peak amplitudes were subsequently referenced to this point. Individual peak-to-peak N1–P2 amplitudes were also measured for responses to both S1 and S2, when present, to allow comparison of the overall magnitude of the response to S2 relative to S1 (this is a better choice for amplitude comparisons than individual components given the differences in the S1 and S2 baselines). The number of response components present for each stimulus condition was also calculated as a percentage of the total number of participants tested within the infant and adult groups. Grand mean ERP waveforms to each of the stimulus conditions were also compared in terms of morphology, mean amplitudes, and latencies.

One-way repeated-measures analyses of variance were used for all statistical comparisons. For adults, the following comparisons were made: (1) peak amplitudes and latencies of the P1, N1, and P2 components that were recorded to the /da_/ /ba_/ and /Da_/ (2) N1–P2 peak-to-peak amplitudes of S1 and S2 stimuli for the /dada/, /daba/, and /daDa/ stimulus conditions, and (3) N1–P2 amplitudes at which S2 amplitudes were expressed as a percentage of S1 amplitudes. For infants, peak amplitudes and latencies of P1, N1, and P2 components were compared for responses elicited to S1 for the /da_/ /daba/, /dada/, and /daDa/ conditions. Newman-Keuls post hoc comparisons were performed for significant main effects. Results for all analyses were considered statistically significant if \( p < 0.05 \). Statistical analyses were not performed for the S1 N2 or any of the S2 components because these components were only consistently present for the /daba/ condition.

RESULTS

Adults

The overall morphology of the waveforms elicited to each of the stimulus conditions was very similar across individual adult participants. For this reason, only grand mean waveforms for this age group are presented. As shown in Figure 1, the grand mean waveforms elicited to /da_/ /ba_/ and /Da_/ show the

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**TABLE 2. Summary of total number of epochs recorded and accepted in infant waveforms elicited in 26 infants (N = 8–9 per stimulus condition)**

<table>
<thead>
<tr>
<th>Stimulus Condition</th>
<th>/da_/</th>
<th>/dada/</th>
<th>/daba/</th>
<th>/daDa/</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total epochs recorded</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>311</td>
<td>335</td>
<td>328</td>
<td>311</td>
</tr>
<tr>
<td>1 SD</td>
<td>32</td>
<td>99</td>
<td>36</td>
<td>49</td>
</tr>
<tr>
<td>Final epochs accepted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>203</td>
<td>236</td>
<td>246</td>
<td>200</td>
</tr>
<tr>
<td>1 SD</td>
<td>53</td>
<td>67</td>
<td>39</td>
<td>63</td>
</tr>
<tr>
<td>Range</td>
<td>146–312</td>
<td>107–335</td>
<td>185–304</td>
<td>102–257</td>
</tr>
<tr>
<td>Artifact rejection rate</td>
<td>35%</td>
<td>30%</td>
<td>26%</td>
<td>39%</td>
</tr>
</tbody>
</table>

The number of accepted epochs was measured after baseline adjustments, ocular corrections, and manual artifact rejection were conducted.

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**Fig. 1.** Grand mean waveforms elicited to /da_/ /ba_/ and /Da_/ at C3 for a total of six adults with normal hearing, whose native language is English. The P1, N1, P2, and N2 components of the obligatory cortical response elicited to these stimuli are indicated on the graph.
typical P1, N1, P2, and N2 components of an adult cortical response, at which N1 and P2 are the most prominent peaks. As shown in Table 3, there were no statistically significant differences in the amplitudes or latencies of the P1, N1, and P2 peaks across these stimulus conditions except for N1 which elicited a larger amplitude to /da_/ and /ba/ compared with /Da_/ (p = 0.021). As shown in Figure 2, the grand mean waveforms elicited to the S1 of /dada/, /daba/, and /daDa/ also showed robust P1, N1, and P2 cortical components. As indicated in Table 4, for S1 stimuli, the N1 and P2 components of the cortical response were present in all adults and a clear P1 component was present in the majority of cases. The mean latencies for these components elicited to S1 were, on average, 52, 103, and 182 msec for P1, N1, and P2, respectively, when pooled across stimulus conditions as shown in Table 5. The mean amplitudes for the components of the P1–N1–P2 complex elicited to S1 ranged from −4.55 to +6.79 µV ([P2]>[N1]>[P1]). Half the adults also had an N2 component with a mean latency and amplitude of 279 msec and −3.97 µV, respectively, averaged across stimulus conditions (Table 5).

The overall morphology of the responses to the change from S1 to S2 (i.e., the ACC) was similar for /dada/, /daba/, and /daDa/ (Fig. 2). The P1, N1, and P2 components were present in all or most cases; however, N2 was not clearly identified for any of the participants (Table 4). In comparison to the cortical response elicited to S1, the mean latencies for the S2 components were slightly longer—66, 133, and 220 msec, for P1, N1, and P2, respectively (Table 5). The mean amplitudes for the S2 P1–N1–P2 complex were smaller overall compared with those elicited to S1 and, in contrast to responses to S1, N1 was larger, on average, than either P1 or P2 (S2 baseline adjusted) (Table 5). When the peak-to-peak amplitude of the S2 N1–P2 was compared relative to the S1 N1–P2 complex for the grand mean waveforms, as shown in Figure 3, the amplitude elicited to /daba/ was 11% greater compared with both /dada/ and /daDa/ (i.e., the ACC elicited to the change from /da/ to /ba/ tended to be larger than the change from /da/ to /da/ and /da/ to /Da/); however, this difference did not reach statistical significance when amplitudes were either compared directly (F[2,10] = 2.524, p = 0.130) or when S2 amplitudes were expressed as a percentage of S1 amplitudes (F[2,10] = 0.772, p = 0.488).

Infants

Because the infant group showed much greater variability compared with the adult group, both the grand mean and individual waveforms recorded in response to /da_/, /dada/, /daba/, and /daDa/ are shown in Figures 4 and 5, respectively. As with the adults, among the infants, the grand mean waveforms elicited to /da_/ and the S1 responses elicited to /dada/, /daba/ and /daDa/, comprised P1, N1, P2, and N2 components; however, in contrast to the adults, all infants had a P1 component, a few infants did not have a clear N1 and 50 to 89% of infants had a clear N2 component (Table 4). Although the morphology of the infant grand mean responses to the S1 stimuli was similar to that of adults, the latencies of the peaks for the infants were, on average, 55 to 120 msec later compared with adults. The mean latencies for the components of the cortical response elicited to S1 were, on average, 113, 206, 307, and 419 msec for P1, N1, P2, and N2, respectively, when pooled across stimulus conditions.

### Table 3. Comparisons of amplitude and latencies for the P1, N1, and P2 components of the slow cortical response to S1 elicited by /da_/ /dada/, /daba/, and /daDa/ in adults using repeated-measures two-way analyses of variance

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>p</th>
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</thead>
<tbody>
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<td>Amplitude</td>
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<tr>
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<td>0.658</td>
</tr>
<tr>
<td>N1</td>
<td>2, 6</td>
<td>6.03</td>
<td>0.025*</td>
</tr>
<tr>
<td>P2</td>
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<td>Latency</td>
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<tr>
<td>P1</td>
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<tr>
<td>N1</td>
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</tr>
<tr>
<td>P2</td>
<td>2, 8</td>
<td>1.06</td>
<td>0.391</td>
</tr>
</tbody>
</table>

*Significant (p < 0.05).
TABLE 4. Percentage of responses present for each stimulus condition for infant (N = 8–9) and adult (N = 6) participants

<table>
<thead>
<tr>
<th>Token</th>
<th>Component</th>
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<th>/dada/</th>
<th>/daba/</th>
<th>/daDa/</th>
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<tbody>
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</tr>
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</tr>
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<td>100</td>
</tr>
<tr>
<td></td>
<td>N2</td>
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<td>0</td>
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</tbody>
</table>

BP; broad positive peak; BN, broad negative peak.

conditions as shown in Table 6. The mean amplitudes for the components of the P1–N1–P2–N2 complex elicited to S1 were larger compared with adults, and ranged from −17.38 to +12.17 μV (relative dominance of the peaks varied with stimulus condition) (Table 6). Unlike that of the adults, the infant grand mean waveform elicited to /da/ (i.e., no ACC predicted) also showed a broad positive (BP) peak at approximately 340 msec (Fig. 4). Fifty percent of the infants had a BP peak and 13% had a broad negative (BN) peak in this latency region (Table 4).

The morphology of the grand mean waveforms elicited to the change from S1 to S2 differed for the three S2 stimuli (Fig. 4). For /daba/, there were three components in the grand mean response elicited by the /ba/ portion of the stimulus—a clearly defined positive peak, a negative trough, and a second broader positive peak. For /dada/, there were only BP and BN peaks elicited to the second /da/ at approximately 600 and 820 msec, respectively. Similarly for /daDa/, broad peaks were elicited to /Da/ at the approximate latencies found for /dada/ but the peaks were much smaller in amplitude in the grand mean waveform.

Because of the individual variability in the waveforms, the grand mean waveforms obscured some of the individual findings that are of interest in a study that is preliminary in nature. For this reason, the components of individual waveforms will be described in detail. An ACC to the change from S1/da/ to S2 /da/, /ba/, or /Da/ would be predicted to be present in the waveform beyond the onset of S2. For /daba/, the response beyond the onset of S2 comprised two positive peaks at approximately 219 and 458 msec, respectively, with a negative trough between these peaks in the region of 331 msec (Table 6). The morphology of the response to the change from /da/ to /ba/ resembled the morphology of the P1, N1, and P2 components of the S1 response; however, the mean peak latencies for the S2 response occurred 116, 107, and 133 msec later compared with the S1 peaks. Unlike /daba/, the components of the responses elicited to S2 in the /dada/ and /daDa/ did not resemble the obligatory onset response to S1. For /dada/, five infants had a first positive peak to the S2 /da/ at approximately 552 msec but none had a discernible S2 N1 peak; only one infant had a second sharper positive peak but it had a latency of 999 msec. For /daDa/, two infants had sharp peaks that resembled the S1 P1 peak at 500 msec but there were no other sharp peaks present. For both /dada/ and /daDa/, some infants had BP peaks at approximately 600–650 msec and a few had BN peaks ranging from 656 to 824 msec in latency. None of the infants had BP and BN peaks in response to /daba/ (Table 4).

As shown in Table 7, statistical analyses comparing the amplitudes and latencies of the cortical components across stimulus conditions revealed a significant effect of stimulus condition for P2 amplitude and trends in the data that did not reach statistical significance for N1 amplitude and P1, N1, and P2 latencies. The N1 and P2 latencies elicited to /da/ tended to be shorter (p ≤ 0.10) compared with other stimuli. P2 amplitude for /da/ was significantly larger compared with /dada/ and tended to be larger when compared with /dada/ and /daDa/. For /dada/, the amplitude of N1 also tended to be larger and the latency of P1 tended to be longer compared with the other stimuli.

TABLE 5. Adults: mean (1 SD) baseline-to-peak amplitude and peak latency measurements for P1, N1, and P2 components of the waveforms elicited to the S1 and S2 portion of the /da/ and /dada/, /daba/, and /daDa/ stimulus conditions are shown

<table>
<thead>
<tr>
<th>Peak</th>
<th>/da/</th>
<th>/dada/</th>
<th>/daba/</th>
<th>/daDa/</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>P1</td>
<td>2.51* (1.72)</td>
<td>2.56 (1.17)</td>
<td>2.20 (1.41)</td>
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<tr>
<td></td>
<td>N1</td>
<td>−4.55 (1.23)</td>
<td>−3.57 (1.93)</td>
<td>−3.36 (1.70)</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>6.79 (2.20)</td>
<td>5.70 (2.11)</td>
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</tr>
<tr>
<td></td>
<td>N2</td>
<td>−4.84 (0.40)</td>
<td>−2.37 (1.92)</td>
<td>−4.05 (2.1)</td>
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<td>N1−P2</td>
<td>11.34 (3.16)</td>
<td>9.19 (3.39)</td>
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</tr>
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<td>S2</td>
<td>P1</td>
<td>1.8 (2.03)</td>
<td>1.66 (1.69)</td>
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<tr>
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<td>N1</td>
<td>−5.87 (2.20)</td>
<td>−5.82 (2.28)</td>
<td>−5.71 (2.18)</td>
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<td>P2</td>
<td>1.64 (1.35)</td>
<td>1.69 (1.79)</td>
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</tr>
<tr>
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<td>N1−P2</td>
<td>7.51 (2.30)</td>
<td>6.69 (2.50)</td>
<td>6.61 (2.65)</td>
</tr>
</tbody>
</table>

The latencies were measured from the onset of the S1 stimulus and from the onset of the change in the stimulus at S2. Mean (1 SD) P1−P2 amplitudes are also indicated. Mean values that represent measurements from fewer than five responses are denoted with an asterisk. The dashed line indicates that no responses were detected.
DISCUSSION

Slow Cortical Response to S1

The cortical responses elicited to S1 in adults were consistent with what is typically reported in terms of morphology and amplitude and latency characteristics—a robust N1–P2 response in all cases and many adults presenting with clear P1 and N2 components. Like adults, infants had obligatory S1 responses to /dada/, /daba/, and /daDa/ that were very similar to each other overall, but unlike adults, infants tended to have shorter latencies and larger P2 components for the /da_/ condition. These differences in amplitude and latency for the infants are likely explained, in part, by the longer ISI used to elicit /da_/, which was actually 2502 msec rather than 2200 msec given that S2 was a silent period.

Čeponienė et al. (1998) found that an increase in ISI from 300 to 700 msec resulted in a statistically significant decrease (8 msec) in N1 latency for 8- to 9-year-old children as a result of the reduced effects of refractoriness. In the present study, N1 latencies were longer by 36 msec, on average, for /dada/, /daba/, and /daDa/ that were very similar to each other overall, but unlike adults, infants tended to have shorter latencies and larger P2 components for the /da_/ condition. These differences in amplitude and latency for the infants are likely explained, in part, by the longer ISI used to elicit /da_/, which was actually 2502 msec rather than 2200 msec given that S2 was a silent period. Čeponienė et al. (1998) found that an increase in ISI from 300 to 700 msec resulted in a statistically significant decrease (8 msec) in N1 latency for 8- to 9-year-old children as a result of the reduced effects of refractoriness. In the present study, N1 latencies were longer by 36 msec, on average, for /dada/, /daba/, and /daDa/ compared with /da_/.

It is possible that overlapping responses to S2 and S1, which are not present for responses to /da_/, also contributed to our larger change in N1 latency given that the change in ISI was comparable for these two studies.

The latencies of the components of the obligatory slow cortical response elicited in 4-month-old infants were significantly prolonged relative to adults indicating immaturity in the cortical response as predicted. One interesting finding of the present study, however, was that the infant responses resembled a mature P1–N1–P2 response in terms of the peaks and troughs present in the waveform and their relative prominence. This finding was somewhat unexpected given that the vast majority
of studies have reported a biphasic waveform with a large positive and negative peak over a latency range of 200 to 550 msec (reviewed by Wunderlich & Cone-Wesson 2006). Studies have shown that ISIs of 1400 to 5000 msec will elicit the N1 component in preschool and school-aged children (Brunneau et al. 1997; Ceponienė et al. 1998; Takeshita et al. 2002); however, the N1 in early childhood is less prominent compared with a mature N1 response. For example, Wunderlich et al. (2006) used the speech stimulus “bad” (200 msec in duration; stimulation rate of approximately 3 to 6 sec) and found that the N1 was present but it was much smaller compared with P2 and N2. We specifically selected this example to allow approximate comparisons with the findings from our study. Wunderlich et al.* used speech parameters similar to what we used in the present study (i.e., long-duration speech stimuli with long ISIs). They used a stimulus duration of 200 msec and ISIs that ranged from 3 to 6 sec, both of which are longer than those used in many other cortical ERP studies. Their stimulus parameters served to optimize the likelihood of eliciting and enhancing P1 and N1 components. Unlike Wunderlich et al. who used ISIs that were even longer than those used in the present study, we found that the overall morphology of our infant P1–N1–P2–N2 response was similar to the adult response but with delayed latencies. Although it is assumed that the general morphology of the P1–N1–P2–N2 is not adult-like until 12 years of age, our findings indicate that it is possible to elicit a cortical response that resembles adult morphology at 4 months of age. Our results suggest that it is possible to record an ACC in infants to a change within a speech stimulus. Can we use the findings of the present study to predict discrimination patterns? The ACC results for /daba/ would support that the infant’s brain can detect a change in the stimulus from /da/ to /ba/ because most of the infants had an ACC. The absence of a clear ACC for /daba/ could be interpreted to mean that the infants did not detect as much of a change in the stimulus compared with /daba/ thus eliciting an attenuated (i.e., some had a P1 response) or absent ACC to the change in the speech tokens. The ACC we elicited to /dada/ is puzzling. We had predicted that both /daba/ and /dada/ would show larger ACCs with distinct components.

### Acoustic Change Complex

The findings of this study support that an ACC can be elicited in adults to /dada/, /daba/, and /dada/. For adults, the differences in ACC magnitude across stimulus conditions did not reach statistical significance; however, the grand mean ACC tended to be slightly larger for /daba/ compared with /dada/ and /dada/ (Fig. 3). The preliminary findings of this study of ACC for infants are encouraging regarding the potential use of the ACC as an index of speech-discrimination ability. This is the first published study that shows that it is possible to record an ACC to changes in a speech stimulus in infants as young as 4 months of age. Our results suggest that a change from the /da/ in the first speech token to /ba/ in the second speech token can consistently elicit an ACC. All infants had an ACC in response to /daba/ and most of these ACCs comprised P1, N1, and P2 components similar to what was recorded at the onset of the S1 token. Fewer infants had the different components of the ACC present in their responses to /dada/ and /dada/; a number of their responses also comprised BP and BN peaks at approximately 320 to 550 msec rather than the distinct P1, N1, and P2 peaks seen earlier in the waveform between 64 and 222 msec for /daba/. Essentially, the responses to /dada/ and /dada/ resembled that of /da/; except for the occasional presence of P1 and N2 components.

Our findings suggest that it is possible to record an ACC in infants to a change within a speech stimulus. Can we use the findings of the present study to predict discrimination patterns? The ACC results for /daba/ would support that the infant’s brain can detect a change in the stimulus from /da/ to /ba/ because most of the infants had an ACC. The absence of a clear ACC for /daba/ could be interpreted to mean that the infants did not detect as much of a change in the stimulus compared with /daba/ thus eliciting an attenuated (i.e., some had a P1 response) or absent ACC to the change in the speech tokens. The ACC we elicited to /dada/ is puzzling. We had predicted that both /daba/ and /dada/ would show larger ACCs with distinct components.

---

**TABLE 6. Infants: mean (1 SD) baseline-to-peak amplitude and peak latency measurements for individual components of the waveforms elicited to the S1 and S2 portion of the /da/, /dada/, /daba/, and /daDa/ stimulus conditions**

<table>
<thead>
<tr>
<th>Peak</th>
<th>/da/</th>
<th>/dada/</th>
<th>/daba/</th>
<th>/daDa/</th>
<th>Mean Amplitude in µV (1 SD)</th>
<th>Mean Peak Latency in msec (1 SD)</th>
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</thead>
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<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
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<tr>
<td>BP</td>
<td>4.80* (1.96)</td>
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<td>374* (86)</td>
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The latencies were measured from the onset of the S1 stimulus and from the onset of the change in the stimulus at S2. Mean (1 SD) N1–P2 amplitudes are also indicated. Mean values that represent measurements from fewer than five responses are denoted with an asterisk. The dashed line indicates that no responses were detected. BP: broad positive peak; BN: broad negative peak.

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*It should be noted that Wunderlich and colleagues used a consonant-vowel-consonant (CVC) rather than the CVCCVs used in the present study, which might account for some of the differences between the findings from these studies.
TABLE 7. Comparisons of amplitude and latencies for the P1, N1, and P2 components of the slow cortical response to S1 elicited by /da /, /dada/, /daba/, and /daDa/ in infants using one-way analyses of variance

<table>
<thead>
<tr>
<th>Component</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>3, 30</td>
<td>0.85</td>
<td>0.477</td>
</tr>
<tr>
<td>N1</td>
<td>3, 28</td>
<td>2.53</td>
<td>0.077</td>
</tr>
<tr>
<td>P2</td>
<td>3, 30</td>
<td>3.19</td>
<td>0.038*</td>
</tr>
<tr>
<td>Latency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>3, 30</td>
<td>2.73</td>
<td>0.062</td>
</tr>
<tr>
<td>N1</td>
<td>3, 28</td>
<td>2.33</td>
<td>0.096</td>
</tr>
<tr>
<td>P2</td>
<td>3, 30</td>
<td>2.63</td>
<td>0.064</td>
</tr>
</tbody>
</table>

*Significant (p < 0.05).

As a result of the preliminary nature of the present study, we did not control for all the factors that are commonly known to affect cortical responses. An everpresent constraint when testing infants is limited test time, which dictates the number of stimulus conditions that can be included in the experimental design. For example, we chose to use only one relatively long ISI and one speech-token duration in the present study so we were unable to investigate the optimal stimulus parameters that might be used to elicit an ACC. Perhaps, if we had used an ISI of 3000 to 4000 msec or a stimulus token of 500 rather than 256 msec, we could have recorded an ACC for /daDa/ that was similar in morphology to that of /daba/. It is possible that variability in refractoriness for individual infants could have contributed, in part, to the variability in response morphology such that the infants who were tested using the /daba/ stimuli had shorter refractory periods than the other infants and thus better morphology of their ACCs. It is also possible that an ISI of 2200 msec is barely long enough to optimize the opportunity to elicit an ACC with multiple peaks, and that the acoustic change in /daba/ was just large enough to elicit a clear ACC. If we had been able to test /daba/, /dada/, and /daDa/ in the same infant (which had been our initial plan), this would have been easier to tease out. The presence of BP and BN peaks in the ACCs for /daba/ and /daDa/ are reminiscent of the infant cortical responses that are most frequently recorded, particularly for ISIs shorter than 1 sec. The presence of a biphasic ACC after an obligatory response to /da/ that contains clear P1, N1, P2, and N2 components lends support to the idea that an ISI longer than 2200 msec would be beneficial for recording ACCs in infants so that the same components of the ACC can be compared across stimulus conditions. However, the presence of multiple peaks versus biphasic peaks in the ACC may in itself reflect that a larger difference in a feature of the stimulus was discriminated or at least detected.

Because of limited testing time, we also did not record responses to both /daba/ and /dada/ to confirm that an ACC can be reliably recorded independent of order of the speech tokens, and to investigate any order effects on the ACC, if indeed there are any such effects. Studies using MMN elicited to similar Hindi contrasts (speech tokens 2, 3, and 9 on the same continuum) have shown differences in the characteristics of the MMN depending on which speech tokens are used for the standard and deviant stimuli in an oddball paradigm (Tsui 2000). It is also a consideration that the /ba/ and /Da/ tokens and the differences in their acoustics features relative to /da/ were not equivalent in terms of eliciting a similar ACC. For example, the ACC may have been more sensitive to the lower burst frequency of /ba/ in /daba/ and not the changes in F2 and F3 for /dada/ and /daDa/. Perhaps, if we had selected a different token within the categorical boundary for /ba/, which does not have a lower burst frequency, such as token 5, we would have found a pattern of results more similar to /daba/ and /dada/. Similarly, if we had selected a different token for /Da/, we may also have elicited an ACC more similar to /daba/. It is also possible that the morphology of the ACC will vary for different consonants that are selected for CV pairings. These are some of the issues that will require further investigation to shed light on the underlying neurological processes that the ACC of infants reflects. The most important finding of the present study is that the presence of an ACC to the change from /da/ to /ba/ was not only apparent at the group level but also at the level of the individual infant. This finding contrasts with MMN, which is typically variable in terms of its presence and morphology across a group of infants.

CONCLUSIONS

These preliminary findings support that it is possible to record an ACC in young infants and provide a starting point for further investigations of the infant ACC and its utility as an index of discrimination. This would involve confirming that the ACCs recorded in the present study can be repeated for a variety of stimuli, determining how much of a change is needed before an ACC can be elicited in infants, and also determining optimal stimulus parameters for measuring ACCs in infants of different ages.

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Address for correspondence: Susan A. Small, School of Audiology & Speech Sciences, The University of British Columbia, 2177 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 1Z3. E-mail: ssmall@audiospeech.ubc.ca

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