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Development of the N1–P2 auditory evoked response to amplitude rise time and rate of formant transition of speech sounds

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Abstract

We investigated the development of weighting strategies for acoustic cues by examining the morphology of the N1–P2 auditory evoked potential (AEP) to changes in amplitude rise time (ART) and rate of formant transition (RFT) of consonant–vowel (CV) pairs in 4–6-year olds and adults. In the AEP session, individuals listened passively to the CVs /ba/, /wa/, and a /ba/ with a superimposed slower-rising /wa/ envelope (/ba^{wa}). In the behavioral session, individuals listened to the same stimuli and judged whether they heard a /ba/ or /wa/. We hypothesized that a developmental shift in weighting strategies should be reflected in a change in the morphology of the N1–P2 AEP. In 6-year olds and adults, the N1–P2 amplitude at the vertex reflected a change in RFT but not in ART. In contrast, in the 4–5-year olds, the vertex N1–P2 did not show specificity to changes in ART or RFT. In all groups, the N1–P2 amplitude at channel C4 (right hemisphere) reflected a change in ART but not in RFT. Behaviorally, 6-year olds and adults predominately utilized RFT cues (classified /ba^{wa} as /ba/) during phonetic judgments, as opposed to 4–5-year olds which utilized both cues equally. Our findings suggest that both ART and RFT are encoded in the auditory cortex, but an N1–P2 shift toward the vertex following age 4–5 indicates a shift toward an adult-like weighting strategy, such that, to utilize RFT to a greater extent.

Keywords

Auditory evoked potential; Consonant–vowel; Development; Speech; Amplitude rise time; Formant transition

1. Introduction

Spoken language processing entails encoding the many acoustic (temporal and spectral) cues afforded by the speech signal in auditory cortex (AC) and perceptually organizing them to enhance intelligibility. The current knowledge about how the relative weighting of acoustic cues changes with development is still a work in progress [3,7,11,12,14,17,20–22]. A study by Nitttrouer et al. [12] supported the premise that children's reliance on the dynamics of formants develops before that of amplitude envelope in phonetic labeling. However, a recent study by Goswami et al. [7] showed that amplitude rise time (ART, how quickly acoustic

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energy changes at speech onset) is crucial for development of language processing. They examined phonetic contrast abilities for synthetic /ba/ and /wa/ consonant–vowels (CVs) that varied along their continuum of ART or rate of formant transition (RFT) in normal and dyslexic children. They reported that normal children were better at phonetic discrimination when the CVs varied in ART but not RFT [7], signifying the importance of amplitude information for phonetic labeling in normally developed children. We should note that similar studies [13,24] on adults have shown that they predominately base their labeling of /ba/-/wa/ on RFT.

These previous, sometimes divergent, behavioral accounts motivated us to assess the neurophysiological causes of developmental shifts associated with weighting of ART and RFT. We measured the N1–P2 auditory evoked potential (AEP) to /ba/ and /wa/ CVs and a /ba/ CV superimposed with the slower-rising /wa/ envelope (/ba/^{wa}) in children (4–6-year olds) and adults. The N1 and P2, which represent synchronous neural activity in the primary and non-primary AC [19], begin to emerge around 3–6 years of age [16,18,20]. Some studies have reported that this AEP complex emerges even later [21], while others place the milestone at a much younger age, ~6 months [4]. These differing accounts may be attributed partly to differences in experimental designs (rate of stimulus presentation, type of stimulus). Also, it is not clear whether the N1–P2 observed in infants [4] originates from the same neural generators that underlie the N1–P2 in older children. Notwithstanding, the magnitude and latency of the N1–P2 are known to reflect changes in spectrum and/or amplitude cues of CVs [8,15]. Thus, studying the N1–P2 developmental dynamics could help explain the maturation of children's weighting of acoustic cues during phonetic categorization.

We hypothesized that the N1–P2 morphology should reflect the weighting of ART and RFT. That is, when phonetic labeling is based heavily on RFT, the N1–P2 amplitude for /ba/^{wa} should be similar to that of /ba/ (similar RFT, different ART) but different from that of /wa/ (similar ART, different RFT). However, if phonetic labeling is heavily based on ART, we should find that the N1–P2 amplitude of /ba/^{wa} similar to that of /wa/ but different from that of /ba/. The first hypothesis is favored for adults. However, we expected children to use ART to a larger extent than adults, such that they may label /ba/^{wa} as /ba/ or /wa/ equally. Hence, in children, the N1–P2 for /ba/^{wa} may be different from those evoked by either /ba/ or /wa/.

2. Materials and methods

2.1. Subjects

Twenty-seven native English speakers were recruited from The Ohio State University via posted flyers and from a subject pool from the Department of Otolaryngology. Subjects were of the following ages: 4–6 years (between 4-years 0-months and 6-years and 11-months; $n=15$, 8 males) and 18–25 years ($n=12$, 6 males). Informed written consent was obtained from each participant, and parental consent was obtained for children. Normal audiometric thresholds for pure tones (250–8000 Hz, <25 dB) were obtained for all participants. All experimental procedures were approved by the Institutional Research Board (IRB) of The Ohio State University.

2.2. Stimuli

Stimuli were recorded using Shure KSM microphone (Shure Inc., Niles, IL) and Tube MP Studio V3 pre-amplifier (ART, Rochester, NY), sampled at 48,000 Hz, and 16 bit from two native English speakers (female: $f_0 = 250\text{Hz}$; male: $f_0 = 125\text{Hz}$). All stimuli were 300ms in duration, low-pass filtered at 12,000 Hz, and of equal RMS power. The stimuli (see Supplemental Figure) consisted of 2 naturally voiced CVs, /ba/ and /wa/, and a natural /ba/

with a super-imposed /wa/ temporal envelope (termed /ba^{wa}). The /ba/ and /wa/ CVs exhibit similar formant trajectory (direction) but the rate of transition of the first and especially the second formant is delayed in /wa/. Thus, /ba/ and /ba^{wa} differed in the temporal envelope but were similar in RFT, and /wa/ differed from /ba^{wa} only in RFT. The envelope superposition for /ba^{wa} was done using the Hilbert transform [1]. The behavioral and EEG testing also included additional CV types to test different hypotheses but are not discussed in this study.

2.3. Procedure

The experiment was optimized for the ERP passive task. Our goal was to show that development of perceptual encoding of acoustic cue weighting is reflected during low-level (bottom-up) auditory processing (in the absence of selective attention). This is hard to demonstrate using behavioral measures alone which require attention. Nonetheless, as a logical supplement, we also conducted a behavioral session to show that these low-level developmental changes transfer to behavior. Future developmental studies should take into account the top-down (selective attention) influence on development of AEP morphologies (e.g., passive vs. active tasks).

To control for order effects, half of the participants in each group began with the behavioral session and the other half began with the EEG session.

2.3.1. Behavior—We measured the classification accuracy of CVs for each subject. Subjects were seated in a sound-attenuated room and wore insert earphones (Etymotic Research ER4, Elk Grove Village, IL). First, each CV was presented separately, and the experimenter labeled the stimuli as /ba/ for /ba/, /wa/ for /wa/, and noise for noise. /ba^{wa} was labeled by the experimenter as a /ba/ “that may not be completely clear”. The noise stimulus was included to control for guessing. That is, if a subject labeled a CV as noise more than 33% of the time, the participant was not included in the final analysis. Three 4-year olds were excluded based on this criterion (six 4–5-year olds remained). Second, each CV type was presented randomly 8 times with instruction to identify whether the subjects heard all stimuli (/ba/, /wa/, /ba^{wa} or noise) as /ba/, /wa/, or noise. Subjects uttered their responses while the experimenter recorded them.

2.3.2. AEPs—Continuous electroencephalogram (EEG) was acquired using a 20-channel cap (10–20 system, BioSemi Active-2 system, Netherlands, sampled at 1024 Hz, with Common Mode Sense and Driven Right Leg passive electrodes serving as grounds). Each CV was presented 50 times in a random order, in 4 blocks, for a total of 200 trials for each CV type (100 in a female voice and 100 in a male voice). A passive listening protocol was followed, during which subjects watched a subtitled silent movie of their choice on a monitor approximately one meter in front of them. Stimuli were presented at a comfortable sound-pressure level (~60–65 dB, according to initial feedback from participants) through the same earphones as the behavioral experiment. A variable inter-stimulus interval of 1.5–2 s was used. The EEG session lasted about 45 min with few minutes breaks between blocks.

2.4. Data analysis

Dramatic differences in behavior and AEPs prompted us to divide the children into two groups, 4–5-year olds (only one of which was 5-year old, $n = 6$) and 6-year olds ($n = 6$).

2.4.1. Behavior—Correct classification for the natural /ba/, /wa/, and the /ba^{wa} (labeled as /ba/) CVs were normalized to percentages of correct responses.

2.4.2. EEG

2.4.2.1. Pre-processing: EEG analysis was conducted using EEGLAB [5] and in-house MATLAB (MathWorks, Inc., Natick, MA) code. Continuous EEG files were average referenced, epoched from -200 ms to $+500$ ms around stimulus onset, and baselined to the 200 ms pre-stimulus interval. Trials containing amplitudes of ± 150 μ V or larger at any channel were rejected. Subsequently, trials were averaged according to each CV type (collapsing over gender to increase number of trials and improve signal-to-noise ratio), and band-pass filtered between 0.5 and 30 Hz using a zero-phase FIR filter. Analysis of the N1 and P2 AEPs were performed at channels Fz, Cz, C3 and C4. The mean number and standard deviation of trials for each group (averaged across CV types) were 150 ± 13 for the 4–5-year olds; 184 ± 11 for the 6-year olds; 192 ± 8 for adults.

2.4.2.2. Peak analysis: Latencies of the N1 and P2 AEPs of the group average waveforms for each CV type were first identified visually at channels Fz, Cz, C3, and C4. The group latency for the N1 was identified as the maximum negative peak between 100 ms and 200 ms after sound onset for children and between 50 ms and 150 ms for adults. The group latency for the P2 was identified as the maximum positive peak between 140 ms and 250 ms for both children and adults. N1–P2 peaks could not be identified at C3 for the 4–5-year olds. Also, for the 4–5-year olds the group-average for two of the CVs did not show a clear N1 reversal (down and up potential), but they did show a deflection. In that case, the N1 and P2 amplitudes were determined as the beginning and end of the deflection, respectively. Subsequently, individual N1 and P2 peaks were automatically identified based on the group and CV type latencies identified above. The N1–P2 latencies at C4 were used to get individual N1–P2 peak values at C3 for the 4–5-year olds.

In younger children, the developing N1 is seen as an emerging small negative dip between the positive P1 and P2 peaks. Therefore, the N1 amplitude in young children is influenced by the amplitudes of the overlapping P1 and P2. To work around this problem the N1–P2 peak-to-peak amplitude, was considered as a more objective measure for comparing AEPs across age.

2.5. Statistical analysis

2.5.1. Behavior—An analysis of variance (ANOVA, general Linear Model of Statistic v. 9.1, StatSoft, OK) was conducted to show whether groups differed in their labeling of the CVs, with variables being group and CV type. The ANOVA tested the percentage that subjects labeled /ba/ as /ba/, /wa/ as /wa/, and /ba/^{wa} as /ba/ correctly. Post hoc tests were based on Fisher's Least Significant Difference (LSD) test.

2.5.2. AEPs—N1–P2 peak-to-peak amplitudes for each channel were contrasted using an ANOVA with two factors: group and CV type. Post hoc analyses were based on LSD test.

3. Results

3.1. Behavior

Fig. 1A shows the percentages of correct CV classification for the three groups. An ANOVA on the correct responses revealed main effects of group ($F_{(2,21)} = 59$, $p < 0.0001$; $\eta_p^2 = 0.85$), and CV type ($F_{(2,42)} = 10.5$, $p < 0.0005$; $\eta_p^2 = 0.33$) and an interaction between the variables ($F_{(2,42)} = 5.6$, $p < 0.0005$; $\eta_p^2 = 0.35$). The group main effect was due to more correct labeling in the 6-year olds ($>97\%$) and adults (99%) than the 4–5-year olds (71%) (post hoc tests, $p < 0.0001$). The CV main effect was attributed to more correct responses for /ba/ and /wa/ ($>92\%$) than /ba/^{wa} (79%) ($p < 0.005$). There was no difference between the percentages of correct responses between /ba/ and /wa/ ($p > 0.5$). Finally, the interaction between group

and CV type was attributed to less accurate labeling of /ba/^{wa} (labeled as /ba/ ~46%; compare to correct labeling of /ba/ or /wa/ which was >80%) in the 4–5-year olds ($p < 0.0001$) but not in the older groups ($p > 0.35$; Fig. 1A). In the 6-year olds and adults, correct labeling of all 3 CVs was above 93%. In short, the 6-year-olds and adults predominately labeled the CVs based on the RFT and ignored changes in ART, while the 4–5-year olds performed well when identifying the CVs with intact ART and RFT (~82%), but had trouble labeling /ba/^{wa} (RFT as /ba/ and ART as /wa/).

3.2. AEPs

Fig. 1B shows AEPs at Fz, Cz, C3, and C4 averaged over all CV types for each group. N1 topographies are shown in Fig. 1B. Fig. 1C (left) shows the N1–P2 peak-to-peak amplitudes evoked by each CV type for each group at Cz. Fig. 1C (right) shows the N1–P2 amplitudes evoked by each CV type averaged across the three groups at channel C4. Notice from Fig. 1A and B, that for children, a positivity (“P1”) dominates fronto-centrally and a negativity (N1) starts to emerge fronto-centrally (more at channel C4) at age 4–5, gets stronger (more bilaterally at C3 and C4) at age 6, and fully dominates fronto-centrally for adults.

3.2.1. Fz—An ANOVA on the N1–P2 amplitudes at Fz revealed only a main effect of group ($F_{(2,21)} = 19.5$, $p < 0.0001$; $\eta_p = 0.6$), and no interaction between the variables ($F < 0.3$). Post hoc analysis revealed that the group main effect was due to larger N1–P2 AEPs occurring in adults compared to children ($p < 0.005$) with no difference between the children's groups ($p > 0.3$).

3.2.2. Cz—An ANOVA on the N1–P2 amplitudes at Cz revealed main effects of group ($F_{(2,21)} = 17.1$, $p < 0.0001$; $\eta_p = 0.62$), CV type ($F_{(2,42)} = 6.0$, $p < 0.005$; $\eta_p = 0.22$), and an interaction between the variables ($F_{(4,42)} = 5.5$, $p < 0.005$; $\eta_p = 0.6$). The group main effect was due to larger N1–P2s in adults compared to children ($p < 0.005$), with no difference between the children groups ($p > 0.2$). The CV main effect was due to larger N1–P2s for /ba/ and /ba/^{wa} compared to /wa/ ($p < 0.01$), with no difference between AEPs for /ba/ and /ba/^{wa} ($p > 0.2$). Finally, the interaction between the variables was attributed to larger N1–P2s occurring for /ba/ and /ba/^{wa} compared to /wa/ only in the 6-year olds and adults ($p < 0.03$). In these groups, the N1–P2s of /ba/ and /ba/^{wa} did not differ ($p > 0.15$). In short, the N1–P2s for the 6-year olds and adults were not different for CVs that had the same RFT and different ART, but differed for CVs of different RFTs. Finally, there was no difference between the emerging N1–P2 of the /ba/, /ba/^{wa} and /wa/ CVs in 4–5-year olds ($p > 0.5$), suggesting a lack of specificity of the N1–P2 AEP at Cz to RFT or ART for this age group.

3.2.3. C3—N1–P2 at C3 exhibited similar behavior as Fz. Therefore, we do not state the statistics.

3.2.4. C4—An ANOVA on the N1–P2 amplitudes at C4 revealed main effects of group ($F_{(2,21)} = 9.5$, $p < 0.005$; $\eta_p = 0.47$), CV type ($F_{(2,42)} = 6.5$, $p < 0.005$; $\eta_p = 0.24$), and no interaction between the variables ($F < 0.5$). The group main effect was due to larger N1–P2s occurring for adults compared to children ($p < 0.01$) with no difference between the children's groups ($p > 0.3$). Interestingly, the CV main effect was attributed to larger N1–P2s occurring for the /ba/ compared to /ba/^{wa} and /wa/ ($p < 0.01$) with no difference between the N1–P2s of the /ba/^{wa} and /wa/ CVs ($p > 0.6$). In short, the N1–P2 at C4 was sensitive to ART differences for all groups. This is opposite to the effect observed at Cz in the older groups.

4. Discussion

Our results reveal that in children 6-years of age and adults the N1–P2 AEP at the vertex reflected the fidelity of RFT weighting. That is, the vertex N1–P2 was influenced by a change in the CVs' RFT but not ART. This was consistent with these groups' behavior, in which they almost exclusively relied on RFT, but not ART, in labeling the /ba/ /wa/ CVs. In contrast, there was no clear difference in the vertex N1–P2 AEP in the 4–5-year olds' in response to changes in RFT or ART, consistent with their chance level labeling of /ba/^{wa}. Interestingly, the N1–P2 at channel C4 (right hemisphere) reflected ART fidelity in all groups – the N1–P2 was influenced by a change in the CVs' ART but not RFT (opposite the effect seen at the vertex). In short, both ART and RFT are encoded in AC, but the emergence of stronger N1–P2 at the vertex points to a shift toward an adult-like weighting strategy, in which children begin to utilize RFT to a greater extent than ART.

This perceptual transition around age 4–6 years coincides with the manifestation of synaptic connections in the superficial layer of the AC [10], that are known to give rise to the N1–P2 complex. It also suggests that the N1–P2 begins to play an important role in encoding rapid spectral change (observed in /ba/ and /ba/^{wa}) within speech. Previous studies reported that the N1 and/or P2 are sensitive to frequency change in the context of CV and vowel–vowel transition [6,8,9]. Martin et al. [9] showed that, in adults, the N1–P2 complex, evoked by a change of spectrum following vowel-to-vowel transition in /ui/, did not change during amplitude decrements. Their results suggest that the N1–P2 evoked by formant transitions reflects cortical frequency encoding, consistent with our results for adults and 6-year olds (the vertex N1–P2 changed with RFT but not ART). Furthermore, the N1 and P2 response have been shown to augment following frequency [2] and voice onset time discrimination training [23], consistent with their roles in coding spectral complexity [20] and rapid spectral change. Thus, the emergence of the N1–P2 at the vertex following age 4–5 may indeed reflect the development of the cortical response associated with fine tuning to spectral cues in sound, which may cause children to develop reliance on spectral dynamics of speech (e.g., RFT).

An alternative explanation to our findings is that literacy-level (experience), as opposed to development, may have caused the children's shift in weighting strategy and AEPs. 4–5-year olds can be classified as pre-readers, while 6-year olds are being explicitly taught about letter-sound correspondences, which may have led to the development of phonemically specified representations. Such an explanation would fit the findings reported by Goswami et al. [7]. They reported that while children who struggle with reading (dyslexic) were poorer than age-matched controls at discriminating /ba/ from /wa/ on the basis of ART, they were not significantly different from younger reading-level matched controls. We should note however, that a comparison between our study and Goswami et al. [7] must be interpreted with caution because the two studies utilized different tasks, a discrimination task (same–different) vs. a labeling task. It is possible that children develop greater sensitivity to both ART and RFT with age (or experience), while at the same time develop a strategy that favors one cue over the other (RFT herein) during phonetic classification.

Our results do not suggest that a lack of a mature N1–P2 AEP is detrimental to speech comprehension. After all, 4–5-year olds understand natural speech well. However, conflicting acoustic cues could have an unfavorable impact on speech processing in children because of their weakly specified phonetic neural representations. Consequently, 4–5-year olds may need congruent acoustic cues in order to correctly label a phonetic sound. For example, when ART and RFT cues of a CV are not aligned with the stored cortical representations of that CV, as in the /ba/^{wa} stimulus, young children fail to integrate the two cues properly and their phonetic labeling suffers. Thus, our findings may suggest that the

emergence of the vertex N1–P2 after age 4–5 allows a mechanism whereby children learn to segregate the cues and favor one over another.

There are two caveats of the current behavioral task: 1 – The 4–5-year olds may have been confused by the instructions. 2 – Number of trials per condition ($n=8$), may have been inadequate. However, while we do advise prudence in future experiments, we are doubtful that these limitations confounded our conclusions, especially when taking into account a recent behavioral-only study that addressed the same question posed here [11]. Nittrouer et al. [11] examined labeling responses of /ba/-/wa/ along ART and RFT continua in 4–5-year olds and adults. When using the /ba/ stimulus with the slowest rising ART (most like /wa/ ART and most analogous to our /ba/^{wa}), 25% (compare to 50% in our study) of 4–5-year olds labeled it as /wa/, as opposed to adults which labeled it as /ba/~100% of the time. Despite this result, they [11] concluded that ART does not influence the /ba/-/wa/ contrast for children. Their conclusion however was based on all /ba/ conditions which included /ba/ CVs with ARTs that were less /wa/-like and more/ba/-like. Nonetheless, we argue that the two studies converge once taking into account the age difference between our 4 and 5-year olds and theirs. In our study, five out of six of the 4–5-year olds were 4-years of age, as opposed to Nittrouer et al.'s [11], in which the age was more equally balanced between 4 and 5 years. If indeed ART is less weighted with age, as advocated in this study, then the greater number of 4-year olds in our 4–5-year old group, compared to Nittrouer's et al. [11], may have skewed the percentage to favor ART weighting in our study more than theirs.

5. Conclusions

Our findings provide evidence that after 4–5-years of age, children weight RFT more than ART (an adult-like strategy) during the /ba/-/wa/ phonetic categorization. This weighting shift toward greater reliance on spectral dynamics coincides with the emergence of the vertex N1–P2 AEP, reflecting synaptic maturation in the superficial layer of the AC. Accordingly, we posit that the period between 4 and 6 years of age represents a critical period in learning spoken language.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Highlights

- 4–5-Year olds assign equal weights for formant and amplitude information.
- 6-year olds weight formant more than amplitude transition, an adult like strategy.
- A developmental shift in phonetic processing takes place around 4–6 years of age.
- The N1–P2 auditory response at the vertex reflects formant transition weighting.
- 4–6 years of age reflects a critical period in learning spoken language.

Fig. 1.

(A) *Behavior*: Percentages of correct classification of the CVs /ba/, /wa/ and /ba/^{wa}, in 4–5-year olds, 6 year olds and adults. Bars represent 1 standard error. (B) *AEPs*: Group averaged waveforms at channels Fz, Cz, C3, and C4 for the 4–5 and 6-year olds and adults, depicting auditory evoked potentials (AEPs) of all CVs (averaged over /ba/, /wa/ and /ba/^{wa}). Vertical dashed lines at 0 ms represent sound onset. (C) Scalp topographies of the N1 wave for all groups. (D, left) The groups' N1–P2 peak-to-peak amplitudes evoked by the CVs /ba/, /wa/, and /ba/^{wa} at channel Cz. (Right) The N1–P2 peak-to-peak amplitudes at channel C4 evoked by the three CVs averaged across the three groups.