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Neural mismatch indices of vowel discrimination in monolingually and bilingually exposed infants: Does attention matter?

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Abstract

Neurophysiological studies of infant speech suggest that mismatch responses (MMRs) have predictive value for later language. Their value, however, is diminished because unexplained differences in the MMR patterns are seen across studies. The current study aimed to identify the functional nature of infant MMRs by recording event-related-potentials (ERPs) to an infrequent English vowel change in internal or final positions of a sequence of ten vowels in six-month-old monolingually- and bilingually-exposed infants. Increased negativity of the MMR (infrequent minus frequent) was found in final compared to internal positions and correlated with an index of increased attention to the final position. This pattern helps explain the overall greater negativity to the speech sounds in the bilingually-exposed female infants. These findings substantially advance our understanding of neural indices of speech perception development and show promise for furthering our understanding of bilingual language development.

Keywords

infant; attention; ERP; speech perception; neural mismatch; responses; bilingualism

1. Introduction

A number of recent studies suggest that Event-Related Potential (ERP) indices of auditory[6] or speech discrimination[15] in infants can serve as markers of later language abilities. Generally, more negative ERP discriminative responses in the first year of life correlate positively with later language measures. These correlations, however, are small to moderate in size. The finding is also somewhat difficult to interpret because some studies have observed increased positivity at frontocentral sites to an auditory sound change[9, 10], whereas others show increased negativity[4, 5]. An understanding of the factors that account for a positive mismatch response (pMMR) compared to a negative MMR (nMMR) is essential for these measures to be able to better inform us regarding speech development. In

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our recent paper, we hypothesized that the pMMR to an infrequent stimulus change (deviant) reflects reduced refractoriness of the underlying neural generators in auditory cortex compared to refractoriness of neural responses to the frequent stimulus (standard) [27]. Repetition of the standard stimulus leads to refractoriness of the neural population firing to the stimulus, seen as decreased amplitude for some ERP peaks [9, 24]. The nonoverlapping neural populations firing in response to the deviant have more time to recover from refractoriness because the inter-deviant interval is longer than that for the repeating standard. Thus, presence of the pMMR indicates the degree to which different neural populations are activated in response to the two stimuli. In contrast, we hypothesize that the infant nMMR indexes discrimination at a higher level. Specifically, a central sound representation (or category) is formulated for the frequently occurring stimulus or pattern [18] and the deviant stimulus is compared to this representation. The degree of difference from the representation is indexed as a negativity at frontocentral scalp sites and this nMMR is equivalent to the mismatch negativity (MMN) observed in older children and adults [11]. Considerable evidence from adults suggests that the process indexed by MMN takes place in auditory cortex with contributions from frontal regions [11, 18, 21, 22, 25]. Attention is not necessary for this change-comparison process (i.e., it occurs automatically). However, attention can influence formation of the standard representation or resolution of the deviant stimulus [32]. In the case of complex acoustic stimuli, such as speech, attention appears to be necessary to discriminate some acoustic differences, particularly if the difference is not relevant in a listener's native language [14].

In the current study, we examined MMR responses in six-month-old infants to a subtle, speech sound contrast ([I] in "bit" vs. [ɛ] in "bet") that is found in English but not in Spanish. The infants came from monolingual (English-only) or bilingual (Spanish-English) households. Some studies of bilingual speech perception suggest differences in the developmental timecourse compared to monolinguals [2, 7, 15], whereas others show little or no difference [1, 3, 8, 31]. In our previous study [28], we had predicted that bilingual infants would show more positive MMR responses, indicating a slower timecourse of English language development. We expected slower development because experience with Spanish can result in less exposure to English speech sounds. Even in the case that the amount of input in a given language (e.g., English) is equivalent, the additional exposure to the phonology of another language will complicate acquisition of a language-specific phonology because the child must first separate the two language systems before he/she can determine which speech sounds are contrastive [2, 8]. In this previous study, we found that the majority of infants showed a positive MMR to the speech contrast [28]. However, the female infants from the bilingual environment showed significantly more negative MMRs than monolinguals or males from bilingual families. With increasing age, monolingual children showed increasing negativity of the MMRs [28], and by four years of age, almost all monolingual children exhibited the negative MMR/MMN, although the positive MMR was still present at left frontal sites at an earlier latency [27]. Our explanation was that the females from the bilingual group were attending more to the speech sounds, resulting in better resolution of the acoustic information, and, therefore, eliciting a larger amplitude nMMR/MMN. This interpretation is consistent with the claim that bilingually-exposed infants need to track the statistical properties of their two languages separately to develop language-specific phonologies, which may result in attentional differences [8].

In the current analyses, we test the hypothesis that attention influences the MMR amplitudes by examining the responses to the standard ([ɛ] vowel) and deviant ([I] vowel) in the internal compared to final position of sequences of 10 stimuli (with eight standard and two deviant repetitions). We predicted that infants would attend more to stimuli in the final position (if they had picked up the pattern) than to the internal positions based on previous research indicating that final is a position of prominence [13]. We also predicted that infants

showing evidence of greater attention to the final position would also show more negative MMRs in the final compared to internal positions. We expected the bilingual female infants to show more negative MMRs similar to our previous finding[28].

2. Methods

2.1. Participants

Nineteen monolingual (mean age = 197, SD = 16.2; 10 females) and 19 bilingual (mean age = 200 days, SD = 22.1; 8 females) from six-to seven months of age were included in the final data analysis. In addition, one male and two female monolinguals were excluded from the final sample due to experimental error, a caretaker's decision not to participate in the ERP study, or noisy data. Two female bilinguals were excluded due to noisy data, as determined by no obligatory P100. Language input was estimated from a caretaker questionnaire, using a seven-point scale for rating input across multiple situations (e.g., home, playground), with 0 indicating all Spanish, 7 indicating all English, and 3 indicating equal Spanish and English input[28]. Four of the bilingual infants received mean scores between 0 and 2.7 (two girls), eleven (three girls) received mean scores between 2.8 and 5.1, and four (three girls) received mean scores between 5.6 and 6.1. All infants were full-term, normal birth history with no family history of cognitive, neurological, speech-language, or hearing deficits in immediate family members. All had passed a newborn hearing screening according to parent report, and most passed a Transient Evoked Otoacoustic Emissions (TPOAE) hearing screening in the lab. All infants in the analyses showed a clearly-defined P100 peak at frontocentral sites. The groups were matched for socio-economic status (SES) with the majority of infants coming from families with a middle-class or above SES.

2.2. Materials and ERP Procedures

The electroencephalogram (EEG) was recorded from a 63-site geodesic net and time-locked to two, 250-ms re-synthesized vowels [ε] and [I] that differed in F1 and F2 formant frequencies (F1, 650 Hz, 500 Hz, F2: 1980 Hz, 2160 Hz, respectively). Pilot studies revealed poor categorization of these vowels by late adult learners of English with Spanish as a first language, and previous studies revealed absent MMN and poor categorization of these vowels in children with specific language impairment[26]. The stimuli were delivered (via Eprime software) in sequences of ten stimuli (trains) with an ISI of 400 ms between stimuli in the train, and 1500 ms between trains, while infants watched a video with the sound muted. Three train types were randomly presented. The deviant stimulus occurred in the 4th and 8th position for 100 trains, in the 5th and 10th position for 50 trains and in the 6th and 10th position for 50 trains, for a total of 1600 standards (80%) and 400 deviants (20%).

The EEG was recorded at a sampling rate of 250 Hz, filtered 0.1–30 Hz and amplified using Netstation 4.1. The impedances of electrodes were maintained at or below 50 μV. Continuous waves were segmented with a pre stimulus duration of 200 ms and 800 ms post stimulus onset and baseline corrected using the pre-stimulus 100 ms amplitude. Any epochs with electrical activity exceeding $\pm 140 \mu V$ at any electrode site were rejected, and bad channels (on 20% of trials) were replaced by spline interpolation. The mean number of epochs in an ERP average for the two groups ranged from 102 to 360 trials for deviant, and from 324 to 911 trials for standard. Epochs (–200 to 800 ms) were averaged for position (1, 2, 3, 4–9, 10) and type (standard, deviant).

2.3. Statistical Analysis

Mixed Analyses of Variance (ANOVAs) were employed with group (monolingual, bilingual), sex (2) and time (2) as factors to examine the amplitude of the response from

320–400 ms and from 520–600 ms for the ERPs. A model of the MMR was constructed from the average of 10 superior (sites 5, 8, 9, 12, 13, 15, 16, 17, 19, 62) and the average of six inferior electrodes (sites 26, 32, 37, 39, 41, 52) (see Fig. 1). Note that the inferior sites, as expected, were negatively correlated with site 9 and the sign was flipped for these sites before averaging with superior sites. These sites were chosen because they correlated highly (greater than $|+/-0.8|$) with left frontal site 9, which showed the largest effects in previous analyses [28]. The 320–400 ms time window showed significant group by sex differences in the previous study [28]. In addition, the grand mean ERPs suggest differences in MMRs in the late time window (520–600 ms). Tukey's pairwise comparisons were used to follow up interactions. Pearson's r was used to examine correlations.

3. Results

The amplitudes of the first two positivities (P200, P350) to the frequent (standard) [e] vowel decline most dramatically (refractoriness), with continued refractoriness apparent for the internal (3rd–9th) positions within the train. The decline is seen as decreased positivity at frontocentral sites and decreased negativity at inferior and mastoid sites (Fig. 2a). An increase in positivity is apparent for the standard in the final (10th) compared to internal positions. We found a three-way interaction of position (internal vs. final), sex and time for the 320 to 400 ms intervals [$F(1, 34)=5.2663$, $p=.02804$, partial $\eta^2 = 0.13$]. Post hoc comparisons revealed greater positivity in the final compared to internal position for both time intervals (320–360 ms and 360–400 ms) only for the male infants ($p < .001$). For the later time intervals (520–600) significant interactions of position by time [$F(1, 34) = 7.09$, $p = 0.011$, partial $\eta^2 = .17$] and sex, position and time [$F(1, 34)=5.0945$, $p=.03053$, partial $\eta^2 = 0.13$] were observed. The standard was more positive in final compared to internal position, particularly from 560–600 ms for the female infants.

3.1 Standard versus Deviant Comparisons

In comparing the deviant to the standard ERPs, for the internal position, a main effect of stimulus [$F(1, 34)=5.77$, $p=.02$, partial $\eta^2 = 0.14$] was observed from 320–400 ms. In general, the deviant was more positive than the standard (see Fig. 2a and b). No main effects or interactions including stimulus were found for the 520–600 ms interval. For the final position, a significant stimulus by sex interaction was seen for the 320–400 ms interval [$F(1, 34)=4.72$, $p=.037$, partial $\eta^2 = 0.12$]; the deviant compared to the standard was relatively more negative for the female compared to the male infants. No significant differences including stimulus were found for the 520–600 ms interval.

3.2. Final versus Internal Positions, MMR

An ANOVA using the subtraction waves (deviant – standard) revealed a significant main effect of position [$F(1, 34)=4.2020$, $p=.04815$, partial $\eta^2 = 0.11$] for the 520–600 ms interval, but no position effects for the 320–400 ms interval. Greater negativity was observed in the final (10th) compared to internal position for the later interval. Two thirds of the participants showed this pattern and there were no differences in this pattern for any of the groups related to gender or to language background (Fig. 2c and Fig. 3).

3.3. Mismatch Response versus Position Comparisons

Those infants who showed greater positivity of the standard in internal compared to final position from 520–600 ms, were also the same infants who showed increased negativity of the MMR in the final compared to internal position [Pearson's ($r = -0.68$, $p = .0001$)] (Fig. 4). It is important to note that there is no relationship between amplitude difference of the standards and amplitude difference of the deviants in internal and final position ($r = -0.10$).

4. Discussion

These findings support our claim that increased attention to the vowel stimuli led to increased negativity of the MMRs, regardless of language experience. We argue that this increased MMR negativity indicates strengthening of the neural representations for relevant vowel cues, which, in turn, allows for change detection by the system indexed by MMN. If infants could not discriminate the vowel contrasts, then the increase in positivity found for the standard in final position would apply to the deviant stimulus, as well. Furthermore, if increased positivity in final position equally applied to standards and deviants, and there were no differences in the amplitude of the MMRs in internal and final position (i.e., infants showed the same magnitude MMRs in both positions), then no correlation would be observed between the difference in amplitude of the standards and the MMRs in internal versus final position.

Strange[30] argues that native listeners develop selective perceptual routines (SPRs) that allow for efficient and automatic detection of native-language speech contrasts. Both behavioral and electrophysiological evidence (specifically MMN measures) support this claim, revealing poorer behavioral discrimination[16] and smaller MMNs without than with attention[14] in non-native or late learners of a language. Our current study with infants suggests that these SPRs are not fully automatized at 6 months of age, and that attention is necessary to support the change-detection process indexed by the MMN measure. The finding of a positive MMR (pMMR) in many of the infants, particularly in internal position, reveals that infant auditory cortex can resolve the acoustic differences between the vowel stimuli. However, we suggest that the presence of this pMMR does not indicate behavioral perception. The pMMR and nMMR/MMN can partially or fully overlap[12, 17], making it more difficult to interpret findings from infant studies. For example, the study by Rivera-Gaxiola and colleagues[23] showing that more negative MMRs in infants were associated with better language scores at later ages could be the result of either attentional or speech discrimination factors. We suggest that using a paradigm similar to ours can help separate the two factors. It will be particularly interesting in future studies to determine to what extent evidence of increased attention to the final position stimuli predicts later language.

With regards to bilingual experience, the current finding suggests that the increased negativity of the MMR in bilingually-exposed female infants noted in our previous paper[28] was due to increased attention to the speech stimuli rather than to superior discrimination compared to the other groups. Essentially, the difference between bilingual and monolingual females disappears in final position. Rather, a sex differences is found in final position, with females showing the more negative MMRs than males. These findings support an important claim made by Curtin and colleagues [8], namely, that monolingual and bilingual children are equipped with the same cognitive and sensory systems for learning language. With attention to the speech, both groups show a similar increase in negativity. The necessity for infants from bilingual households to separate the two languages may lead to them paying more attention to speech[8]. It is possible that less exposure to the English vowels allows them to maintain novelty, and attracted infant attention for a longer period of time. The sex differences observed in the study confirm previous studies suggesting more rapid brain maturation for female than male infants[29].

A number of studies have argued that bilingual experience leads to enhancement of processing in some cognitive areas (including attention; see [19]), even as early as two-years of age[20]. Our findings do not directly test this claim, but they do suggest that bilingual experience leads to differences in how attention is allocated to speech early in development. Longitudinal data will be necessary to determine whether these early differences are related to later attentional skills.

5. Conclusions

Our findings substantially extend our understanding of neural correlates of speech perception development, and how they are modulated by attention. The findings of these analyses are consistent with our hypothesis that the bilingually-exposed female infants showed more negative MMRs in our previous study[28] because they were attending more to the speech stimuli. Our modified oddball paradigm, with internal and final deviants, shows promise for understanding the relationship between attentional processes and the development of speech perception, and can help further understand speech perception differences in bilingual language development and deficits in language impaired populations.

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Highlights

We explored the functional nature of infant neural mismatch responses (MMRs) to an English vowel change in bilingual compared to monolingual infants.

We compared MMRs in the internal versus final positions of a stimulus sequence.

Increased negativity of the MMR was found in the final position.

We hypothesized that infants paid more attention to the vowels in the final position.

Figure 1.
Electrode Site Positions. Sites used in the analyses are outlined. Superior sites are towards the middle, inferior sites around the edge, and nose at the top.

Figure 2.

ERPs to Vowel Stimuli. The upper panel shows potential amplitudes to the standard /e/ stimulus in the first, second, third, fourth-ninth and 10th positions in the train at frontocentral sites (red and orange) and inferior sites (black). The middle panel shows amplitudes to the deviant in the 4–9th position and the 10th position. The bottom panel shows the subtractions between amplitudes to the deviant and the standard in the 4–9th position and in the final position.

Figure 3.

Mismatch Amplitudes by Train Position. Amplitude of MMR from 560–600 ms post-vowel onset for each infant in the internal compared to final positions. Markers to the left of the line are those showing greater negativity in final compared to internal position.

Figure 4. Correlation of Standard and MMR by Position. Amplitude of the final standards minus internal standards (y-axis) plotted against amplitude of the final MMRs minus internal MMRs (x-axis).