Chapter 6
Neurophysiological Studies of Mandarin Lexical Tone Acquisition in Early Childhood

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Abstract Mismatch negativity (MMN) is an event-related potential (ERP) component used as an index for automatic auditory change detection. MMN can be elicited even when the participant does not pay attention to the stimuli (e.g., while they are reading a book or watching a silent movie). Thus, MMN serves as an excellent tool for assessing auditory discrimination, especially in infants and children with limited attention or motivation. Although MMN is well established in adults, the polarity and latency of mismatch responses (MMRs) in infants are highly inconsistent across studies. This chapter aims to provide a comprehensive review of a series of MMN studies for Mandarin lexical tone and to understand the effects of age and degree of deviance on MMRs in infancy and early childhood. The findings here suggest that MMN and positive MMR index different functional characteristics and may provide information on when and how speech perception becomes automatic at different developmental stages in children. The transition from positive to negative MMRs may serve as a neural marker for the early identification of atypical language development in children.

6.1 Background

The ability to produce and understand language is a distinctive characteristic that separates humans from other species. There are around 5000–7000 spoken languages in the world. Each language uses a specific set of phonemes (such as vowels and consonants) to form syllables. It is generally agreed that infants are born with the capacity to learn any language in the world. However, exposure to an ambient language, starting in the womb, may alter phonetic perception shortly after birth. For

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example, Moon, Lagercrantz, and Kuhl (2013) found that infants at birth responded to native and non-native vowels differently and suggested that neonates were capable of learning phonetic contrasts in the womb. A large body of evidence has shown that infants between 6 and 12 months of age show improved perceptual sensitivity to native phonetic contrasts and reduced sensitivity relative to non-native ones (Cheour et al., 1998; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Polka & Werker, 1994; Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Werker & Tees, 1984). These findings suggest that, during the first year of life, early experiences with language shape the perception and production of speech sounds, allowing infants to become language-bound listeners. Moreover, speech perception ability measured in early infancy may predict later language development (Guttorm, Leppänen, Hamalainen, Eklund, & Lyytinen, 2010; Guttorm et al., 2005; Molfese & Molfese, 1985, 1997). Thus, a better understanding of the milestones of language acquisition may shed some light on early identification of and intervention for language and reading problems in children.

Recent advances in the use of noninvasive brain techniques in cognitive neuroscience, including electroencephalography (EEG)/event-related potentials (ERPs), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI), have allowed researchers to examine language processing in an infant's brain to investigate language acquisition in the initial developmental stage of life. This chapter aims to review a series of electrophysiological studies to investigate developmental changes in discriminating the lexical tone, an essential suprasegmental feature for syllables in tonal languages, from early infancy to childhood. The ultimate goal of this chapter is to provide a better understanding of developmental changes in speech perception in early childhood and the relationship between these changes and later language and reading acquisition.

6.2 Mismatch Negativity (MMN) and Positive Mismatch Responses (P-MMR)

Näätänen et al. (1997) demonstrated that speech-sound representations can be probed using a cortical response called mismatch negativity (MMN), which is an ERP component that reflects automatic auditory change detection. MMN is typically obtained in a passive auditory oddball paradigm, wherein a deviant in certain aspects of sound features occurs infrequently in a sequence of repetitive homogeneous (standard) stimuli (Näätänen, Kujala, & Winkler, 2011; Näätänen, Paavilainen, Rinne, & Alho, 2007). In adults, MMN is usually observed as a frontal distributed negativity peaking between 100 and 250 ms after stimulus onset by subtracting ERPs for the standard stimuli from those for the deviant. MMN is mainly generated in the auditory cortex for any discriminable change in simple acoustic and complex phonetic stimulus features (Alho, 1995; Hsu, Lin, Hsu, & Lee, 2014). MMN amplitude increases, whereas peak latency decreases, with the increasing magnitude of stimulus deviation

(Näätänen et al., 2007; Sams, Paavilainen, Alho, & Naatanen, 1985). The accuracy of behavioral sound discrimination has been demonstrated to be strongly correlated with the MMN amplitude in normal and clinical populations (Kraus et al., 1993; Lang et al., 1995). Most importantly, the MMN can be elicited even when a participant is not paying attention to stimuli (e.g., when reading a book or watching a silent movie). Thus, MMN has been suggested as an index for auditory change detection in the pre-attentive stage and may serve as an excellent tool for assessing auditory discrimination, especially for infants and children with limited attention or motivation. By using the MMN paradigm, Cheour and colleagues 1998 reported that Finnish 12-month-old infants revealed an enhanced MMN response to their native vowel contrast, compared with their MMN response to the non-native Estonian vowel contrast, even when the non-native contrast had a more distinct acoustic difference (Cheour et al., 1998). This finding is congruent with behavioral evidence and suggests that language-specific speech-sound memory traces develop between 6 and 12 months of age.

It is worth noting that, although studies have reported MMN in infancy in response to pitch changes (Cheour et al., 2002), duration changes (Brannon, Libertus, Meck, & Woldorff, 2008; Brannon, Roussel, Meck, & Woldorff, 2004), and phonetic changes (Cheour-Luhtanen et al., 1995; Cheour et al., 1998; Kushnerenko et al., 2001; Martynova, Kirjavainen, & Cheour, 2003), infant MMN usually persists for a longer interval in a relatively late time window in comparison with the typical MMN in adults. Meanwhile, many studies have reported the positive mismatch response (P-MMR) between 200 and 400 ms, instead of MMN, in response to speech and non-speech changes in infants (Dehaene-Lambertz & Baillet, 1998; Dehaene-Lambertz & Dehaene, 1994; Friederici, Friedrich, & Weber, 2002; Jing & Benasich, 2006; Leppänen, Eklund, & Lyytinen, (1997); Morr, Shafer, Kreuzer, & Kurtzberg, 2002; Novitski, Huotilainen, Tervaniemi, Näätänen, & Fellman, 2007). For example, Leppänen et al. (1997) observed P-MMR peak between 250 and 350 ms in newborns in response to the pure tone change. Dehaene-Lambertz and Dehaene (1994) reported that 3-month-old infants showed P-MMR peaking at approximately 390 ms in response to initial consonant changes (/ba/vs. /ga/). Friederici et al. (2002) examined the mismatch response to syllables varying in vowel durations (short/ba/ vs. long/ba:/) in 2-month-old infants and found P-MMR peaking at approximately 400 ms, especially when considering long syllables as the deviance.

The nature of P-MMR remains unclear. Some researchers have associated the presence of P-MMR to maturational factors, since P-MMRs were mainly found in infancy. Leppanen et al. (2004) reported that newborns with more mature traits of cardiac measures tend to exhibit larger P-MMR peaking at the latency of 150–375 ms. He, Hotson, and Trainor (2007) examined the brain responses in 2- to 4-month-old infants to infrequent pitch changes of piano tones. Their data showed an increase in the left-lateralized positive slow wave at 2 and 3 months of age, whereas, a faster, adult-like MMN was only presented in 3- to 4-month-old infants. Trainor et al. (2003) reported that the mismatch response transformed from positive to negative, between 2 and 6 months of age. Kushnerenko, Ceponiene, Balan, Fellman and Näätänen (2002) longitudinally traced the development of pitch change detection in a group of infants from birth until 12 months of age. Their data showed that the adult-like MMN stabilized between 3 and 6 months of age, although substantial variability in MMN within the same infant across ages was observed. These findings imply that the adult-like MMN becomes prominent, whereas the P-MMR diminishes with advancing age and neural maturation, which may play a role in the developmental changes of mismatch responses to auditory change detection.

Other studies have suggested that the presence of P-MMR may reflect a difficulty in auditory discrimination, without the maturation factor being the sole cause, since, P-MMR is not restricted to infancy, and additionally, has been reported in young children and adults. For example, Maurer and colleagues reported 6- to 7-year-old children exhibiting P-MMR to frequency (1000 Hz vs. 1060 or 1030 Hz) and phoneme ('ba' vs. 'ta' or 'da') deviances, which is substantially smaller, and presented in a shorter inter-stimulus interval (ISI) than those deviances used in most studies. Additionally, children at risk of dyslexia tend to exhibit a more positive P-MMR than their age-matched controls (Maurer, Bucher, Brem, & Brandeis, 2003). Ahmmed, Clarke and Adams (2008) reported 7- to 11-year-old children showing P-MMR to 2% frequency deviance relative to a 1000 Hz standard, with relatively short ISI (400 ms). Children with specific language impairment required more than 10% deviance for generating MMN, whereas their age-matched controls, without any impairments, required only 2 to 5% deviance for generating comparable MMN amplitudes. Moreover, P-MMR may be observed in adults when the deviance is extremely difficult to discriminate. Kuo and colleagues (2014) examined the impact of spectral resolution on MMN by using naturally spoken Mandarin tones and cochlear implant (CI) simulations, with variations in the number of frequency channels as the stimuli. The one-channel CI-simulated Mandarin tone deviance elicited P-MMR in adults with normal hearing, whereas CI simulation with more than eight channels and speech-sound deviance elicited typical MMN (Kuo, Lee, Chen, Liu, & Cheng, 2014). The results indicated that stimulus-related factors such as short ISI, and smaller deviance, limiting the discriminability between standard and deviant frequency, determine the elicitation of P-MMR. Morr et al. (2002) reported the small deviance (1000 vs. 1200 Hz) elicited P-MMR in infants younger than 12-month-old and the adult-like MMN could not be found until 4 years old. Conversely, the large deviance (1000 vs. 2000 Hz) elicited adult-like MMN in most of the participants from the youngest age group (2–7 months of age). The coexistence of P-MMR small deviance and MMN to large deviance at the same age supports that the magnitude of deviance is one of the decisive factors of MMR polarity. Furthermore, children with specific language impairment or hereditary risk of dyslexia tend to elicit P-MMR or smaller MMN, which suggests that the polarity of MMRs, additionally, depends on the linguistic characteristics of individuals (Ahmmed et al., 2008; Datta, Shafer, Morr, Kurtzberg, & Schwartz, 2010). Garcia-Sierra and colleagues quantified the number of words encountered daily by infants to investigate how language input modulates speech perception using MMR as the readout. Their results indicate that 11- to 14-month-old infants exposed to lower language input elicited P-MMR to relatively difficult English /ta/ vs. /pa/ contrast, whereas those exposed to higher language input elicited MMN (Garcia-Sierra, Ramirez-Esparza, & Kuhl, 2016). In summary, P-MMR is mainly found in young infants or children with disadvantaged language background, especially, for discriminating smaller deviances. These factors should be taken together into consideration when investigating the development trajectories of MMR/P-MMR patterns for Mandarin lexical tone changes.

6.3 MMN Studies of Mandarin Lexical Tone Acquisition

Mandarin Chinese is a tonal language that utilizes pitch variations at the syllable level for determining lexical meaning. For example, by applying one of four tones confers distinct meanings to the syllable *yi,* e.g., *yi1* ‘clothes’; *yi2* ‘aunt’; *yi3* ‘chair’; *yi4* ‘easy’. The four lexical tones are categorized phonologically as a high-level tone (T1), a high-rising tone (T2), a low-dipping tone (T3), and a high-falling tone (T4). A number of studies have suggested that pitch contour and pitch height are crucial for characterizing Mandarin tones (Gandour, 1983; Gandour & Harshman, 1978; Jokisch & Jensen, 2007; Klimesch, Sauseng, & Hanslmayr, 2006; Lin et al., 2007). In terms of pitch contour and direction, T2 and T3 are more acoustically similar than T1 and T3. Behavioral studies with tonal discrimination and identification tasks have confirmed that T2 and T3 are more often confused with each other compared with other tonal pairs (Gandour, 1983; Gandour & Harshman, 1978).

Previous ERP studies have used the MMN paradigm to investigate brain responses to lexical tone changes. Luo et al. (2006) first examined MMN responses of the initial consonants (*bai1*, *sai1*, *dai1*, *tai1*) and the lexical tone changes (*bai1*, *bai2*, *bai3*, *bai4*) in native Mandarin speakers. An opposite pattern of hemisphere lateralization was found for the MMN elicited in response to the lexical tone and the consonant contrasts. Regardless of the magnitude of deviance, tonal changes elicited MMN of a larger magnitude and stronger dipole strength in the right hemisphere, whereas the segmental changes elicited greater responses in the left hemisphere. Moreover, ERP studies have indicated that the magnitude of deviance in lexical tone changes affects the latency and amplitude of MMNs (Chandrasekaran, Krishnan, & Gandour, 2007; Cheng et al., 2013; Lee et al., 2012; Tsang, Jia, Huang, & Chen, 2011). For example, the acoustically distinct T1/T3 contrast yielded a larger MMN with an earlier peak latency than the acoustically similar T2/T3 contrast. However, the effect of acoustic similarity on MMN was exclusively found in native Chinese speakers, but not in native English speakers (Chandrasekaran et al., 2007).

Hsu et al. (2014) performed MEG to investigate the neural substrates underlying the MMN elicited by Mandarin lexical tone changes. Infrequent deviants, T1 and T2, were embedded in a chain of a frequent standard, T3, to induce large and small lexical tone changes, respectively. Consistent with ERP studies, the magnetic mismatch response (MMNm) to lexical tone changes was sensitive to the size of deviance. To be more specifically, the acoustically distinct T1/T3 contrast elicited an earlier and larger MMNm than did the acoustically similar T2/T3 contrast. This confirmed that the T1/T3 contrast was easier to discriminate and, therefore, revealed a much more pronounced MMNm response than did the T2/T3 contrast. However, such an effect of the size of deviance was found in the left hemisphere, but not the right hemisphere, suggesting a left hemispheric dominance of the MMNm on Mandarin lexical tone changes (but see Yu, Wan, & Li, Ch. 4 this volume). The left lateralization of the lexical tone MMNm was further supported by the distributed source analysis of the MMNm generator, particularly for the large deviant (T1/T3 contrast). It was concluded that a native Mandarin speaker's MMNm response to lexical tone changes was initially generated in the superior temporal gyrus (STG) in both hemispheres. A greater left lateralization in the STG and middle temporal gyrus was found in hearing large deviance, indicating a left hemisphere dominance for detecting large lexical tone changes. This study also revealed that the laterality decreased as the differences between the standard and deviant sounds became less discriminable. In addition, the neural generators of a lexical tone MMNm could be seen in several frontal regions. For example, activities in the left anterior insula and right anterior cingulate cortex were only involved in MMNm responses to the T1/T3 contrast, but not in those to the T1/T3 contrast; these findings suggested that these two regions are involved in the switching of attention to the salient changes. In contrast, right ventral orbital frontal cortex activation was only found in the T2/T3 contrast, but not the T1/T3 contrast, and has been associated with involuntary amplification or functional inhibition mechanisms.

Most studies on the speech perception of infants focused on the phonological development of consonants and vowels. There is scarce information on when and how infants learn lexical tones. Only a few studies have addressed this issue by using the speech discrimination paradigm to investigate the lexical tone perception in infants with different language backgrounds (tonal versus non-tonal language exposure) (see also Tsao and Liu, Chap. 10. this volume). Although some mixed findings have been reported, it is generally agreed that the development of lexical tone perception in infants undergoes a progression similar to that charted for consonants and vowels. For example, Mattock and Burnham (2006) tested Thai lexical tone discrimination in Chinese- and English-learning infants at 6 and 9 months of age by the conditioned head-turn procedure. They found that Chinese infants remain sensitive to Thai tonal contrasts at both time points, while English infants showed declined discrimination of lexical tones at 9 months of age. Their findings suggested that tonal language-learning infants displayed a perceptual narrowing for lexical tones within the first year of life, even for tones not from their native language Yeung, Chen, and Werker (2013) examined English-, Cantonese-, and Mandarin-learning infants' discriminability of Cantonese tones. All three groups exhibited a distinct preference at 4 months of age. Consistent with the results reported by Mattock and Burnham (2006), English-learning infants were not able to discriminate the same tone contrast at 9 months of age. However, Mandarin- and Cantonese-learning infants displayed language-specific differences in tone preferences at both age points, suggesting that the language-selective perception of lexical tones with tonal language learners emerged from at least 4 months of age.

Notably, acoustic distinctiveness plays an important role in the acquisition of lexical tones. Studies on the development of speech production have suggested that T1 and T4 production are mastered earlier than T2 and T3 (Hua & Dodd, 2000; Li

& Tompson, 1977; Lin, Huang, Huang, & Hsuan, 2008). Three-year-old Mandarin-speaking children easily confuse T3 with T2 in the picture-pointing task (Wong, Schwartz, & Jenkins, 2005). By using the head-turn procedure, Tsao (2008) reported that 12-month-old infants discriminated the T1/T3 contrast more accurately than the T2/T3 and T2/T4 contrasts. These findings suggested that acoustic discriminability plays an important role in the development of lexical tone sensitivity. In addition, Tsao (2017) explored the developmental trend of discriminating T1/T3, T2/T3, and T2/T4 contrasts in Mandarin-learning infants at 6–8 and 10–12 months of age. The data revealed that Mandarin-learning infants could discriminate all three contrasts at both age points. However, they showed improved sensitivity in discriminating the T1/T3, the most salient tone contrast, at 10–12 months of age, whereas no such improvement was found for the less salient contrasts (T2/T3). Altogether, tone language-learning infants developed more accurate representations of the lexical tone around 12 months of age. Furthermore, the language background of infants and acoustic salience of speech units both play critical roles in modulating the time courses of lexical tone acquisition.

Only a few studies have addressed the development of lexical tone sensitivity with ERPs. Lee et al. applied the multi-deviant oddball paradigm with T3 as the standard and T2 and T1 as small and large deviants, respectively, to explore how neural maturation and acoustic saliency modulate MMRs in adulthood, infancy, and childhood (Cheng et al., 2013, 2015; Hsu, Lee, & Liang, 2016; Lee et al., 2012). Cheng et al. (2013) applied the same set of stimuli to further explore MMRs to lexical tone changes in newborns and 6-month-old infants. ERP data from newborns were collected within 13 days of birth, while they were asleep. For newborns, the large deviant (T1/T3 contrast) elicited P-MMRs in 300–500 ms on the left frontal site (F3), while the small deviants (T2/T3 contrast) did not result in any significant MMR. Six-month-old infants were subgrouped according to their status during ERP recording; ten infants were awake and 13 were sleeping. The data from awake 6-month-old infants showed significant MMN to T1/T3 in 150–250 ms and P-MMR to T2/T3 in 300–450 ms. With respect to sleeping 6-month-old infants, no significant MMR was found. The data, obtained using electrophysiological recording techniques that do not require infants' overt responses, suggested that the acoustic saliency effect could be evident as early as at birth. In addition, MMRs to a large deviant lexical tone contrast transited from P-MMR at birth to an adult-like MMN at 6 months of age. These findings suggested that 6-month-old infants were able to automatically discriminate Tone 1 and Tone 3, and the polarity transition of MMRs may be used to reflect the maturation of speech perception.

Cheng's follow-up study examined the development of MMRs to Mandarin lexical tones from 12 to 24 months of age (Cheng & Lee, 2018). As the adult-like MMN to T1/T3 contrast has been found at 6 months of age, the sustained MMNs presented at 12, 18 and 24 months were naturally expected. The most critical observation is when the T2/T3 contrast elicits the adult-like MMN. The data revealed that T2/T3 contrast elicited P-MMRs at 12 and 18 months of age but showed no significant MMR at 24 months of age. In fact, by using the same set of stimuli, the large deviant T1/T3 contrast elicited MMN at 4, 5, and 6 years of age, but the small deviant T2/T3 contrast only elicited P-MMR in the 5- and 6-year-old groups. Yang et al. (2015) also applied the same paradigm to examine the MMR to lexical tone changes in children with or without attention-deficit/hyperactivity disorder (ADHD). Both children with ADHD (mean age 9.15 years) and their age-matched group (mean age 10.82 years) showed typical MMN for the large deviant (T1/T3). However, for the small deviant (T2/T3), the control group showed P-MMR between 200 and 350 ms, while the ADHD group revealed no MMR but late discriminative negativity (LDN). Liu, Chen, and Tsao (2014) examined the developmental changes in MMRs to the synthesized lexical tone pair /i2/ and /i3/ in adults, preschoolers (mean age 3.40 years), and school-aged children (mean age 8.57 years). Although the data from adults showed the typical MMN at 185–335 ms, the two groups of children did not show MMR but showed LDN in the later time window. The stimuli used by Liu et al. (2014) were comparable to the small deviant used by Cheng et al. (2013) and Lee et al. (2012).

Taken together, the findings indicate that the acoustically salient contrast T1/T3 elicited typical MMN in infants at as early as 6 months of age, while the acoustically similar contrast T2/T3 elicited P-MMR from birth to 18 months of age and then elicited no MMR from 2 to 4 years of age. For children aged 5–10 years, whether T2/T3 could elicit significant MMR remains controversial across studies. The absence of MMR at certain ages has been reported in other studies. For example, Morr et al. (2002) reported that the large frequency change (1000 vs. 2000 Hz) elicited MMN in infants aged 3–47 months. However, the smaller frequency change (1000 vs. 1200 Hz) elicited P-MMR in groups aged under 12 months, but no significant MMR could be found between 13 and 47 months. To account for the presence and diminution of P-MMRs in development, Shafer, Yu, and Datta (2010) claimed that the P-MMR indexed detection and encoding of the acoustic properties of a stimulus in afferent (input) connections to the primary auditory cortex. Thus, the P-MMR may reflect a greater recovery of P1 from refractoriness of the neural populations firing to the deviant compared with the standard (Kushnerenko et al., 2007; Shafer et al., 2010). He et al. (2007) showed that, although these two types of mismatch responses could coexist in three-month-old infants, they could be separated using different settings of band filters. Their data demonstrated that the adult-like MMN became apparent while the slow positivity diminished as infants gradually mature from two to four months of age (He, Hotson, & Trainor, 2007). Therefore, the positivity could potentially mask the negativity owing to overlapping latencies. Studies have shown that the P-MMR typically decreased in amplitudes with increasing age and was generally absent by 8 years of age (Datta et al., 2010; Shafer et al., 2010), except for very fine discriminations (Ahmmed et al., 2008). The presence of P-MMR in infants might not be due to a larger P-MMR but due to the absence of MMN overlapped with the P-MMR. This also suggests that, at some point in time, the two types of responses might cancel each other and show a null effect for a specific contrast at a specific time point during maturation.

6.4 MMRs to Lexical Tone Changes in Children with Difficulties in Learning to Read

Reading has been one of the most remarkable skills for human beings for acquiring and exchanging information in daily life. Unfortunately, across languages, approximately 2–10% of the children experience difficulties in learning to read, a condition called developmental dyslexia, despite normal intelligence and good educational opportunities. Empirical evidence suggests that phonological recoding is the most critical component in learning to read, especially in the early phases of reading acquisition (Share, 1995; Sprenger-Charolles, Siegel, Bechennec, & Serniclaes, 2003). It is widely believed that impaired phonological processing is the key deficit in developmental dyslexia (Snowling, 2000).

Indeed, phonetic perception in infancy has been associated with later language development (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Tsao, Liu, & Kuhl, 2004), which suggests that perceptual learning provides a foundation for later and more abstract language learning (Werker & Yeung, 2005). Kraus et al. (1996) reported a nearly absent mismatch response to deviant consonant–vowel syllables in learning-impaired children compared to normal controls. Moreover, this result was correlated with behavioral discrimination of rapid changing speech stimuli (Kraus et al., 1996). Schulte-Korne, Deimel, Bartling, & Remschmidt, 2001 observed that the MMN to speech sounds (/ba/vs. /da/) in boys with dyslexia was attenuated but not absent (Schulte-Korne et al. (2001)). Bonte et al. used the MMN paradigm to study the implicit processing of phonological regularities in children with and without reading difficulties (Bonte, Mitterer, Zellagui, Poelmans, & Blomert, 2005; Bonte, Poelmans, & Blomert, 2007). An enhanced MMN response to non-words with a high versus low phonotactic probability was found in children with normal reading abilities. However, children with dyslexia did not show this sensitivity to phonotactic probability. These findings imply that MMN might serve as a neural marker for early identification of children at risk of language delay and reading difficulty.

Chinese is characterized as a morphosyllabic writing system. The basic Chinese written unit, namely the character, is constructed by a combination of stroke patterns and radicals within a constant square-shaped space. As Chinese orthography contains no representations at the phonemic level, some researchers believe that there is a closer connection between graphic forms and meanings in Chinese and that phonological knowledge may not be crucial in learning to read. Some studies have suggested that Chinese dyslexia may arise from deficits in visual-spatial analysis (Huang & Hanley, 1995; Siok, Spinks, Jin, & Tan, 2009); in contrast, other studies have demonstrated that both rapid automatized naming and phonological awareness performance predict Chinese children's reading performance, even after controlling for participants' IQ, parent's education, and socioeconomic status (Ho, Chan, Chung, Lee, & Tsang, 2007; Ho, Leung, & Cheung, 2011; Hua Shu, McBride-Chang, Wu, & Liu, 2006). Older readers with dyslexia performed poorer in phonemic awareness than the typically developing young readers with matched reading abilities did (Goswami et al., 2010). Zhang et al. (2012) examined the categorical perception of lexical tone in children with or without developmental dyslexia. Both typically developing and dyslexic groups showed MMN to the across- and within-category deviants. However, the categorical perception effect—that is, the enhanced MMN to the across-category deviants compared with that to the within-category deviants—was found in the typically developing group, but not in children with dyslexia. These data also indicate that children with dyslexia may have a general deficit in the categorical perception of lexical tones.

Children with dyslexia and those with ADHD have some similar learning characteristics. As observed for children with ADHD, those with dyslexia may exhibit inattention or distractibility in the classroom because reading activities are demanding, thus resulting in fatigue and inability to sustain concentration for the entire class. Furthermore, children with ADHD may also have reading dysfluency which negatively affect reading comprehension and cause academic failure that similar to that in dyslexic children. Therefore, it may be difficult for parents and teachers to distinguish between ADHD and dyslexia, especially for those who have little experience with these two types of learning disorders. Yang et al. (2015) measured the MMRs to lexical and pure tone changes in children with or without ADHD. Specifically, different ERP could be used to index the auditory changes detection at different stages of attentional control, including the pre-attentive change detection indexed by MMR, the involuntary orientation of attention indexed by P3a, and the orientation of attention for further evaluation reflected by LDN. Unlike dyslexic children who show reduced MMN to speech lexical tone (Zhang et al., 2012), children with or without ADHD show no MMN differences. This finding suggests that children with ADHD have no problems in developing phonological representations for lexical tones to induce MMRs in the pre-attentive stage. However, children with ADHD did show attenuated P3a and enhanced LDN to both the pure tone and lexical tone changes than did their controls, which indicated their deficits in involuntary attention switching and voluntary attentional reorienting while processing auditory deviations. This speculation was further supported by a significant correlation analysis in which children with higher ADHD tendency, indexed by parents' and teachers' ratings of children's ADHD symptoms, tended to show a greater attenuation in P3a amplitude. In addition, Chen, Tsao, and Liu (2016) conducted a longitudinal study to investigate the development of MMR to lexical tone changes (T2/T3) in late-talking children and children with typical language development (TLD) at 3, 5, and 6 years of age. The late-talking children were subdivided into persistent language delay (PLD) and late bloomer (LB) groups based on their language performance at 4 years old. The group difference was mainly found at 3 years old, in which the typically developing children showed no typical MMN in the early time window (185–335 ms), while both late-talking groups (PLD and BL) showed P-MMR. Congruent with the study of Liu et al. (2014), LDN, but no adult-like MMN was observed in TLD children in the later time window at all ages indicating that children at these ages could not automatically discriminate between T2 and T3 at the pre-attentive stage. For the PLD group, the P-MMR was present at 3 years old, and no MMR was observed at later ages. Given that P-MMR has been used to reflect speakers' immature or poor phonetic representations, the data suggested that the development of fine-grained lexical tone representations were delayed in children with PLD between 3 and 5 years old. Critically, the MMR measured in children aged 3 years correlated with the language outcome in those aged at 6 years, thus suggesting that brain responses of lexical tone discrimination may predict children's later language performance. Taken together, these findings implied that these ERP components, MMR, P3a, and LDN may serve as neural markers for early identification of children at risk of language and reading development impairment and for the differential diagnosis for ADHD and dyslexia.

6.5 Conclusion

This chapter provides an overview of a series of studies that applied the multiple-deviant paradigm to investigate the developmental trajectories of MMR to Mandarin lexical tones in adults and in developing populations including infants, toddlers, preschoolers, and school-age children with or without learning disabilities. The data from adults demonstrated that the amplitude and latency of MMN could be modulated by the size of the deviances. Specifically, acoustically distinct T1/T3 contrast yielded a larger MMN with an earlier peak latency than did the acoustically similar T2/T3 contrast (Chandrasekaran et al., 2007; Cheng et al., 2013; Hsu et al., 2016). Moreover, the neural substrates of MMNs to lexical tone changes were mainly generated from the left hemisphere (Hsu et al., 2014). The data measured in early infancy showed that the T1/T3 contrast elicited P-MMR in newborns. The adult-like MMN first presented in infants at 6 months of age and was sustained in infants at 12, 18, and 24 months of age and in preschoolers from 4 to 6 years of age. Small deviant T2/T3 did not elicit MMR in newborns. P-MMR to T2/T3 was found in infants at 6, 12, and 10 months, but not in those aged 24 months. These studies observed the coexistence of MMN and P-MMR in the same age group when children responded to different magnitude of deviances. The findings of the transition from a predominantly positive to a predominantly negative response supported the existence of multiple MMN mechanisms. The adult-like MMN became more prominent, whereas the P-MMR diminished as age increased. Given that P-MMR was more likely to be observed in infants at younger age, especially in response to less discriminable changes, literatures have suggested that the presence of P-MMR reflects an immature brain response to changes. Conversely, a more mature brain response was reflected by MMN, which has been used to index the automatic auditory change detection. Our data suggested that the MMR (positive to negative) might provide information on whether speech perception by children is an automatic process at various developmental stages. Furthermore, a few studies have reported the absence of MMR to lexical tone changes in children with language delay or reading difficulties. These findings are compatible with the behavioral evidence that for Mandarin Chinese, the awareness of lexical tone showed a relatively stronger association with Chinese reading, than did the awareness of initial consonants (McBride-Chang et al., 2008; Shu, Peng, & McBride-Chang, 2008), suggesting that suprasegmental perception may be particularly important in exploring Chinese reading development. Further studies to examine the development of MMRs to different Mandarin syllabic features in typically and atypically developing children will be critical for the early identification of children with language impairments.

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