Categorical perception of Mandarin lexical tones in language-delayed autistic children

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Abstract

Enhanced pitch perception has been identified in autistic individuals, but it remains understudied whether such enhancement can be observed in the lexical tone perception of language-delayed autistic children. This study examined the categorical perception (CP) of Mandarin lexical tones in 23 language-delayed autistic children and two groups of non-autistic children, with one matched on chronological age (*n* = 23) and the other on developmental age in language ability (*n* = 23). The participants were required to identify and discriminate lexical tones. A wider identification boundary width and a lower between-category discrimination accuracy were found in autistic children than their chronological-age-matched non-autistic peers, but the autistic group exhibited seemingly comparable performance to the group of developmental-age-matched non-autistic children. While both non-autistic groups displayed a typical CP pattern with enhanced sensitivity to between-category tone pairs relative to within-category ones, such a CP pattern was not observed in the autistic group. These findings suggest among language-delayed autistic children with a developmental age around four, CP is still developing. Finally, we found CP performance correlated with language ability, indicating autistic children's language disability might be predictive of their poor CP of speech sounds.

Keywords: autistic children, categorical perception, tone language, language ability, Mandarin, lexical tones

1. Introduction

Categorical perception (CP) refers to a phenomenon where the formed categories affect the perception, which is often reflected by better perceptual discrimination between things belonging to different categories than those falling within the same category (Goldstone & Hendrickson, 2010). In the classical paradigm of CP, there are two types of tasks—identification and discrimination. Ideally, CP can be reflected by step-like boundaries in identification function and peaks in discrimination function across category boundaries (Repp, 1984). As a salient characteristic of speech perception, CP plays a crucial role in the process of speech representation. One thing to note: some types of speech sounds are not categorically perceived (e.g., level tones and steady vowels; Francis et al., 2003; Fry et al., 1962). Surrounded by numerous sound variants, CP allows listeners to perceive speech sounds across the category boundary with higher sensitivity than within-category variations to map continuous acoustic signals onto discrete categories, which is known as the CP for speech sounds (Liberman et al., 1957). Previous studies suggest that individuals who have difficulties with language (e.g., developmental language disorder) often show speech CP deficits (e.g., Collet et al., 2012). For autistic individuals, despite many of them having poor language abilities, enhanced perception of low-level information is frequently reported in this population (Mottron & Burack, 2001; Mottron et al., 2006). As the CP of speech sounds in autistic individuals remains understudied, especially the CP of lexical tones in tone-language autistic speakers, the current study investigated the CP of lexical tones in autistic individuals who speak a tone language, Mandarin Chinese.

1.1 Development of categorical perception of speech sounds

Infants are able to discriminate different speech contrasts within and beyond the phonological inventory of their native language (Eimas et al., 1971; Kuhl, et al., 2006). With increasing language experience, the perception of native phonemes will be enhanced, accompanied with the non-native ones being ruled out. A categorical manner in perceiving both segments and suprasegments in native language has been observed in children as young as four years old (Ma et al., 2021). However, the fully developed CP at the fine-grained level is a late bloomer that takes a comparatively long time to grow into maturation. Specifically, previous studies on CP of segments showed that the adult-like CP pattern did not emerge until late childhood (e.g., Flege & Eefting, 1986; Xi et al., 2010), while CP of suprasegments took around six years of age to become fully mature (e.g., Chen et al., 2017; Xi et al., 2010). These findings indicate that CP development is not accomplished at one stroke, but polished by enriching language experience.

Weakened CP is often observed in individuals who have received a diagnosis of language disorders. It is long-established that individuals with developmental language disorder (DLD) have difficulties with CP, as illustrated by their lower identification or discrimination abilities relative to the comparison groups (Collet et al., 2012; Quam et al., 2021; Schwartz et al., 2013; Sussman 1993). The CP performance of individuals with DLD is usually compared with that of another clinical group, dyslexic individuals (Gerrits & de Bree, 2009; Robertson et al., 2009; Snowling et al., 2019). For instance, Robertson et al. (2009) investigated the perception of a /b/ to /d/ continuum in children with dyslexia or DLD. In addition to significantly weaker ability in discriminating stops exhibited by both DLD and dyslexic groups relative to the comparison group with normal language ability, the DLD group showed significantly weakened CP than the dyslexic group, which was confirmed by a longitudinal study by Snowling et al. (2019). Two primary explanations for the difficulty in CP have been proposed. First, the problem with CP is thought to correlate with difficulties in mapping the acoustic information to phonological representations (Gathercole & Baddeley, 1990; Sussman 1993). Second, the poor CP performance may be attributed to the allophonic mode of perception: showing high sensitivity in discriminating allophones rather than phonemes (Collet et al., 2012; Serniclaes et al., 2004). For CP in autistic individuals, previous studies showed inconsistent findings (Chen & Peng, 2021; Stewart et al., 2018; Wang et al., 2017; You et al., 2017). Unlike those with DLD or dyslexia, autistic individuals often show enhanced low-level information processing despite having language impairments (Mottron et al., 2006). A preserved CP pattern has been detected in non-tonal language autistic speakers' perception of consonants and vowels, more specifically diphthongs (e.g., French speakers in You et al., 2017; English speakers in Stewart et al., 2018). While there is evidence that steady vowels (i.e., monophthongs) are not perceived categorically (e.g., Fry et al, 1962; Pisoni, 1973), Chen et al. (2019) suggests that vowels could be perceived in a CP manner when diphthongs are involved. By contrast, Wang et al. (2017) found autistic speakers of Mandarin (a tone language) showed impaired CP of lexical tones. For CP of lexical tones see the next section.

1.2 Categorical perception of lexical tones in Mandarin autistic speakers

For tone languages, lexical tones are the distinctive pitch patterns carried by syllables, which is an essential suprasegmental feature in contrasting lexical meanings (Francis et al., 2003). For example, in Mandarin, /yi/ (the standard romanization of Mandarin Chinese) with a high-level tone means "clothes" (Tone 1), /yi/ with a rising tone means "aunt" (Tone 2), /yi/ with a dipping tone means "chair" (Tone 3), and /yi/ with a falling tone means "wing" (Tone 4). CP of lexical tones is a complex question which can be somewhat language and/or contrast-dependent. As for the issue of being contrast-dependent, analogous to the differences observed between vowels and stop consonants (Pisoni, 1973), Francis et al (2003) found that level tones in Cantonese (another tone language) are not likely perceived categorically, while the evidence was more uncertain about contour tones. In Mandarin, on the other hand, there was stronger evidence of CP for lexical tones.

Normally, Mandarin speakers tend to perceive lexical tones categorically, with enhanced sensitivity to between-category contrasts while ignoring subtle within-category variations (e.g., Peng et al., 2010; Wang, 1976; Xu et al., 2006). Tone language speakers start to discriminate lexical tones at a fairly early stage of language acquisition. For example, six- to eight-month-old Mandarin infants have been found to perform at above chance level in distinguishing lexical tone contrasts (Tsao, 2017). With increasing language experience, the perceptual systems of native Mandarin children are tuned to rule out irrelevant tonal variations beyond native phonological contrasts (Best et al., 1995; Chen et al., 2017; Kuhl, 1991; Kuhl et al., 2008). By the age of three, they exhibit considerably high accuracy of Mandarin tone perception, reaching around 90% correct for minimal pair trials, except for the dipping tone (about 70% correct; Wong et al., 2005), while by the age of six, they demonstrate adult-like lexical tone perceptual competence (Chen et al., 2017).

For CP of lexical tones in autistic individuals, it is reasonable to suppose this population might encounter difficulties from two aspects. First, being exposed to the language environment benefits the process of 'statistical learning', and facilitates a higher degree of CP of native phonological contrasts (Kuhl et al., 2003; Saffran et al., 1999). As autistic individuals may receive reduced speech input due to communication deficits, especially in the verbal domain, they may be put at a developmental disadvantage. Second, as suggested by the Weak Central Coherence theory (WCC, Frith, 1989; Happé & Frith, 2006), autistic individuals tend to possess superiority in processing single-dimensional information at the expense of global integration of multi-dimensional information. To perceive Mandarin lexical tones, both acoustic pitch information and phonological information need to be processed simultaneously. Therefore, autistic individuals who are less likely to integrate the information at two levels may encounter difficulties with CP of lexical tones.

Nevertheless, recent research on CP of lexical tones in autistic speakers of tone language has shown inconsistent results (Chen & Peng, 2021; Wang et al., 2017). Adopting the passive oddball paradigm, Wang et al. (2017) examined the CP of Mandarin tones in autistic children (mean age = 10.4) and those without autism matched on both chronological age and intelligence quotient (IQ) using a Tone 2 – Tone 4 continuum. They found that autistic children showed equivalent mismatch negativity (MMN) for both between- and within-category deviants, while non-autistic children exhibited enhanced MMN responses to between-category deviants. The findings illustrated a lack of phonemic boundary between phonological pitch contrasts in autistic children, and the authors claimed that autistic individuals showed impaired CP of lexical tones (Wang et al., 2017). This conclusion, however, should be interpreted with caution since no behavioural tasks were involved in this study. The passive paradigm without focal attention requirement might be insufficient for examining the phonological processing of speech sounds in autistic individuals. It was to test this that Chen and Peng (2021) adopted two behavioural tasks, namely identification and discrimination, and examined the CP performance in autistic adolescents without language delay (mean age = 13.9) and those without autism matched on both chronological age and working memory. The autistic and non-autistic groups showed comparable CP performance, illustrating an intact CP mode of lexical tones in autistic adolescents. Thus, Chen and Peng (2021) argued that the CP of lexical tones was not inherently impaired in autistic individuals. However, the authors posited that the finding of an intact CP pattern in autism was limited to adolescents without language delay. Given the heterogeneity within the autistic spectrum, studies that test the CP of lexical tones in younger autistic individuals and those with low language functioning are needed to obtain a more comprehensive picture of autism.

Meanwhile, Chen and Peng (2021) showed that the degree of CP of lexical tones was related to the language ability. Specifically, autistic participants with better language ability exhibited a narrower perceptual boundary width. The positive correlation between phonological processing capacity and language ability has also been observed in some other studies investigating the CP of segments (Bishop et al., 2004; Constantino et al., 2007; Stewart et al., 2018). For instance, Stewart et al. (2018) tested five language measurements and the CP of stops (/g/ - /k/ continuum) on autistic adults and controls matched on chronological age and nonverbal IQ, revealing correlations between CP performance and verbal abilities including reading, lexical decision, and verbal IQ. Therefore, it is not clear whether the intact CP pattern found in Chen and Peng's (2021) autistic participants without severe language delay can be observed in those with low language functioning.

1.3 The current research

To address the research gaps, the present study investigated lexical tone processing among Mandarin-speaking autistic children with low language functioning. It has been suggested that the degree of CP of lexical tones in Mandarin-speaking children gradually develops with increasing language experience (Chen et al., 2017), and chronological age and/or language ability might be the key factors affecting CP performance. To better control these two factors respectively, we recruited two comparison groups: one composed of non-autistic children matched with autistic children on chronological age, and the other made up from non-autistic children matched with autistic children on developmental age in language ability. As the low degree of CP of lexical tones has been found to be associated with poor language ability (Chen & Peng, 2021), autistic children with low language functioning might experience difficulties with CP of lexical tones. We therefore expect significantly worse CP performance from the group composed of autistic children whose language ability lagged behind their chronological-age-matched non-autistic peers. In addition, if language ability does play a role in the CP of lexical tones of autistic children, we hypothesize that the autistic group will show comparable performance with the developmental-age-matched non-autistic group.

Taken together, we focus on the factors that affect CP performance among Mandarin-speaking language-delayed autistic children, with the following two questions to be particularly pursued: (a) Do language-delayed autistic children show a different CP pattern compared with their chronological-age-matched or developmental-age-matched non-autistic counterparts? (b) Does the degree of CP in autistic children correlate with their language abilities?

2. Method

2.1 Participants

The current study recruited 23 language-delayed autistic and 46 non-autistic children. Non-autistic children were matched with autistic children based either on chronological age (n = 23) or developmental age in language ability (n = 23). Developmental age, a measure of language ability expressed in an age unit, was assessed by three subtests of the Simplified Chinese Version of the Psycho-education Profile-3rd Edition (Yu et al., 2019), whose norms were based on results from 865 non-autistic children in mainland China. The subtests, including 78 items, have been widely used in mainland China to assess receptive and expressive language abilities, and cognitive verbal ability in autistic children. Based on the raw scores of the subtests and his/her chronological age, each autistic child would obtain a developmental age in language ability in reference to the chronological age of non-autistic children with comparable language ability.

All three groups of child participants were native Mandarin speakers. The children in the autistic group were diagnosed by qualified paediatricians or child psychiatrists in local hospitals on the basis of the fourth or the fifth edition of the *Diagnostic and Statistical*

Manual of Mental Disorders (American Psychiatric Association, 2000, 2013). The clinical diagnosis of autism spectrum disorder was further confirmed using three metrics. Specifically, five out of 23 autistic children's diagnoses were confirmed using the Autism Diagnostic Observation Schedule-2 (Lord et al., 2012), 11 autistic children's diagnoses were confirmed by the Childhood Autism Rating Scale (Ozonoff et al., 2005), and the Chinese version of the Autism Spectrum Quotient-Children's Version (Auyeung et al., 2008; Sun et al., 2019) was adopted for the rest of children in the autistic group. Moreover, non-autistic children reported no physical, psychological, or cognitive abnormalities. Autistic children were recruited through <service centers catering for autistic individuals redacted for peer review>, while non-autistic children were recruited via flyers sent to primary schools/kindergartens or advertisements posted on social media platforms (e.g., WeChat). Two screening pre-tests were administered to avoid the inclusion of children who had difficulties in understanding the two behavioural CP tasks (identification and discrimination tasks). Only those who met the criteria were allowed to proceed to the formal tests (see Supplementary Material 1 for details). All the participants met the accuracy criterion for the identification task. Three autistic children failed to meet the criterion for the discrimination task, leaving 20 autistic children for the analyses of the discrimination data. Table 1 provides an overview of participants. Both autistic subgroups had similar chronological age as the children in the chronological-age-matched non-autistic group ($t = 0.18$, $p = 0.861$; $t = 0.46$, $p = 0.650$), but significantly lagged behind this comparison group in terms of developmental age in language ability (ps < 0.001). Meanwhile, the two autistic subgroups showed similar developmental age in language ability to the developmental-age-matched non-autistic group ($t = -0.61$, $p = 0.548$; $t < -0.01$, $p = 0.997$). Specific data on socioeconomic status were not recorded.

Table 1. Descriptive characteristics of participants in two autistic subgroups performing identification and discrimination tasks, respectively, and in two non-autistic groups.

		Autistic group (identification)	Autistic group (discrimination)	Chronological-age-matched non-autistic group	Developmental-age-matched non-autistic group
Number (male)		23 (18)	20 (16)	23 (14)	23 (13)
Chronological age (SD)		7.35 (1.15)	7.44 (1.09)	7.32 (0.88)	4.36 (0.66)
Chronological age range		5.67-9.75	5.75-9.75	5.92-9.67	3.33-5.50
Developmental age (SD)		4.20 (1.15)	4.37 (1.12)	N/A	
Developmental age range		2.17-5.94	2.17-5.94		
Language abilities	CV (SD)	56.74 (14.20)	59.05 (13.33)		
	EL (SD)	47.70 (16.08)	49.90 (15.96)		
	RL (SD)	46.39 (14.90)	48.35 (14.60)		

Note: CV = cognitive verbal ability; EL = expressive language ability; RL = receptive language ability.

2.2 Community involvement

Child participants, their caregivers, and members of the autism community were not involved in the design or implementation of the study. The performance of child participants was disseminated to their caregivers.

2.3 Task and procedure

Two CP tasks, the identification test and the discrimination test, and stimuli involved in the current study are the same as those in Chen et al. (2017). A detailed description is provided in the Supplementary Material 1. Approval of the research was granted by the Human Subjects Ethics Sub-committee at The Hong Kong Polytechnic University (HSEARS20210222007).

2.4 Scoring and data analyses

For the identification test, boundary position and boundary width were calculated. For the discrimination test, between- and within-category discrimination accuracy was calculated (Jiang et al., 2012; Xu et al., 2006). See the Supplementary Material 2 for the calculation methods.

Statistical analyses were conducted using analysis of variance (ANOVA) in R, employing the afex package (Version 4.0.5). For the identification data, separate ANOVAs were performed for each of the dependent variables (boundary position and boundary width) for the comparisons between autistic children and their chronological-/developmental-age-matched non-autistic peers. For the discrimination data, two-way Group (autistic vs. chronological-age-matched non-autistic vs. developmental-age-matched non-autistic group) × Category Type (within- vs. between-category) repeated measures ANOVAs were conducted for the dependent variable, discrimination accuracy. Post-hoc pairwise comparisons were further performed using the lsmeans package with Bonferroni adjustment (Lenth, 2016) to verify whether there were across-category differences for the three groups of children, and to examine the group differences within each category (within- and between-category). Hedges' *g* effect sizes were calculated for the pairwise comparisons (Hedges & Olkin, 1985). In addition, linear regression models were built to investigate the influence of language abilities (expressive and receptive language abilities, and cognitive verbal abilities) on the degree of CP among autistic children.

3. Results

3.1 Identification results

The derived boundary position and width of identification for the three groups of children are shown in Table 2. If a participant had a boundary width greater than 2.5 SD above the group mean, he/she would not be included in further analyses. One autistic child whose boundary width reached 14.28 was excluded, leaving 22 autistic children for the analyses of identification data. Figure 1 displays the overall identification curves for the remaining children in the three groups.

Table 2. Boundary position and width of identification in autistic, chronological-age-matched non-autistic, and developmental-age-matched non-autistic groups.

	Autistic group	Chronological-age-matched non-autistic group	Developmental-age-matched non-autistic group
Boundary position (SD)	5.12 (1.16)	5.52 (0.51)	5.59 (0.93)
Boundary width (SD)	2.22 (0.88)	1.03 (0.33)	2.34 (0.93)

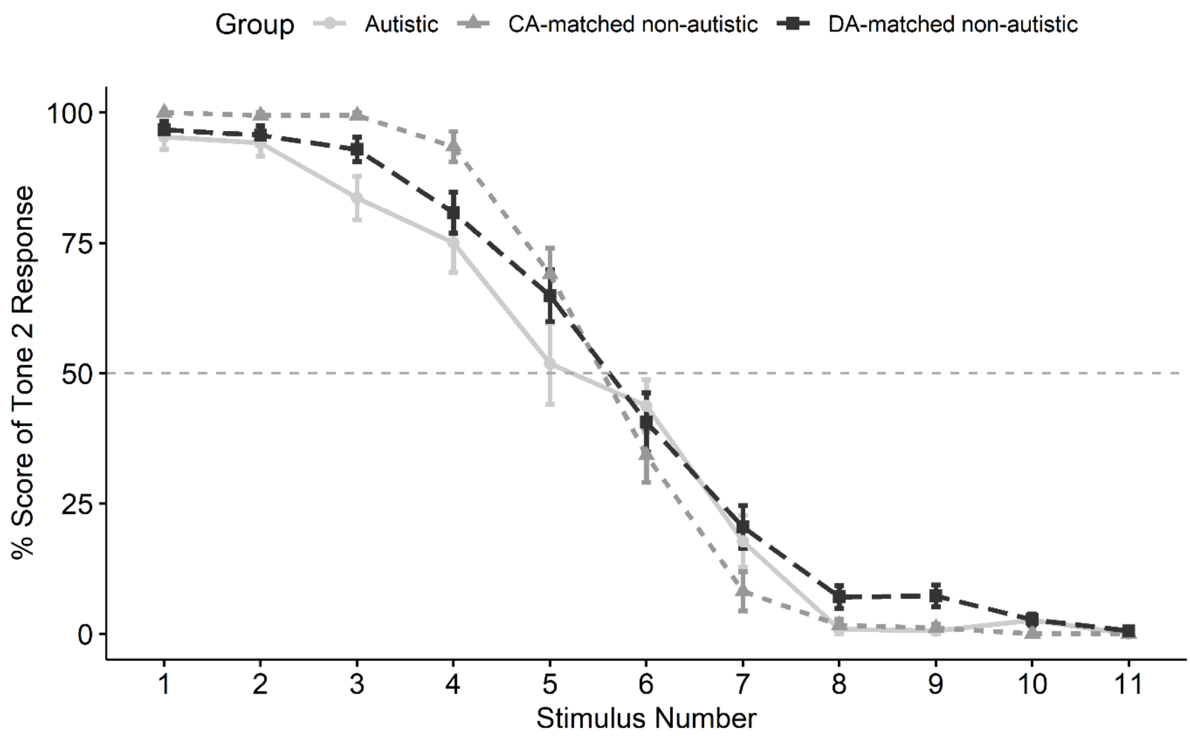

Figure 1. The identification curves of Tone 2 responses in three groups. Error bars: ± 1 standard error.

The ANOVA on boundary position revealed no significant effect of group, suggesting that the boundary position did not differ among the autistic and the two non-autistic groups ($F(2, 65) = 1.72$, $p = 0.188$, $\eta^2_G = 0.05$).

ANOVA on boundary width revealed a significant effect of group ($F(2, 65) = 20.90$, $p < 0.001$, $\eta^2_G = 0.39$). Post hoc pairwise comparisons showed that relative to the chronological-age-matched non-autistic group, the autistic group had a much wider boundary width ($t = 5.27$, $p < 0.001$, $SE = 0.23$, $g = 1.79$). However, the autistic and developmental-age-matched non-autistic groups exhibited a similar boundary width ($t = -0.53$, $p = 1.000$, $SE = 0.23$, $g = -0.13$).

3.2 Discrimination results

The discrimination accuracy of the between- and within-category tone pairs among the three groups are shown in Figure 2. In general, the children in the chronological-age-matched non-autistic group performed better than those in the autistic and the developmental-age-matched non-autistic groups. Statistical analysis revealed a significant two-way interaction of Group × Category Type ($F(2, 63) = 5.84$, $p = 0.005$, $\eta^2_G = 0.07$), and there were significant main effects of Category Type ($F(1, 63) = 45.06$, $p < 0.001$, $\eta^2_G = 0.22$) and Group ($F(2, 63) = 6.97$, $p = 0.002$, $\eta^2_G = 0.12$). For the significant main effect of Group, post hoc pairwise comparisons showed that relative to chronological-age-matched non-autistic children, autistic children had a lower discrimination accuracy ($t = -3.54$, $p = 0.002$, $SE = 0.48$, $g = -0.71$), while autistic children and their developmental-age-matched non-autistic peers had similar discrimination accuracy ($t = -0.891$, $p = 1.000$, $SE = 0.48$, $g = -0.19$), which was further analyzed under different category types respectively. For the between-category type, autistic children performed worse than chronological-age-matched non-autistic children in discrimination of between-category tone pairs ($t = -3.65$, $p = 0.002$, $SE = 2.80$, $g = -1.09$), but they exhibited comparable performance to developmental-age-matched non-autistic children

(t = -0.90, p = 1.000, SE = 2.80, g = -0.26). For the within-category type, there was no difference among the three groups of children in discrimination accuracy (ps > 0.05). Moreover, the interaction effect of Group × Category Type was analyzed under different groups to examine whether there was difference between within- and between-category discrimination accuracy within each group. Post hoc pairwise comparisons revealed that the between-category tone pairs generated a much higher discrimination accuracy than the within-category tone pairs for the chronological-age-matched non-autistic group (t = 6.75, p < 0.001, SE = 1.82, g = 1.76) and the developmental-age-matched non-autistic group (t = 3.14, p = 0.003, SE = 1.82, g = 0.79), but not for the autistic group (t = 1.89, p = 0.064, SE = 1.95, g = 0.51).

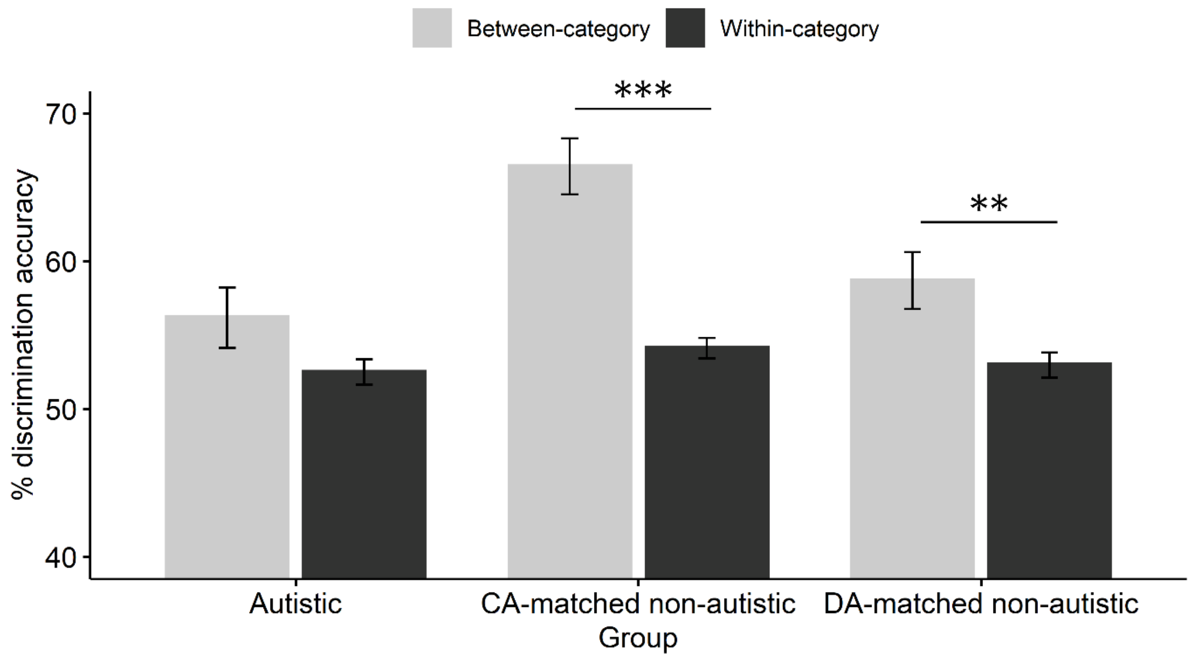

Figure 2. Discrimination accuracy of the between- and within-category tone pairs for autistic, chronological-age-matched non-autistic, and developmental-age-matched non-autistic groups. Error bars: ± 1 standard error.

3.3 Linear regression results

Linear regression analyses were conducted to examine the relationships between predictors (cognitive verbal ability, receptive language ability, and expressive language ability) and two measures for the degree of CP (boundary width of identification and discrimination accuracy of between-category pairs) in autistic children. As shown in Figure 3, for boundary width, cognitive verbal ability, receptive language ability, and expressive language ability were found to be significant predictors for the degree of CP (all *p*s < 0.05). Specifically, the autistic children with higher cognitive verbal ability, receptive language ability, and expressive language ability had a narrower boundary width than those with lower cognitive verbal ability, receptive language ability, and expressive language ability, respectively. For the discrimination accuracy of between-category pairs, receptive language ability was detected to be a significant predictor ($p < 0.05$). The autistic children with higher receptive language ability were more accurate in discriminating between-category pairs than those with lower receptive language ability. A table of regression coefficients is provided in the Supplementary Material 3.

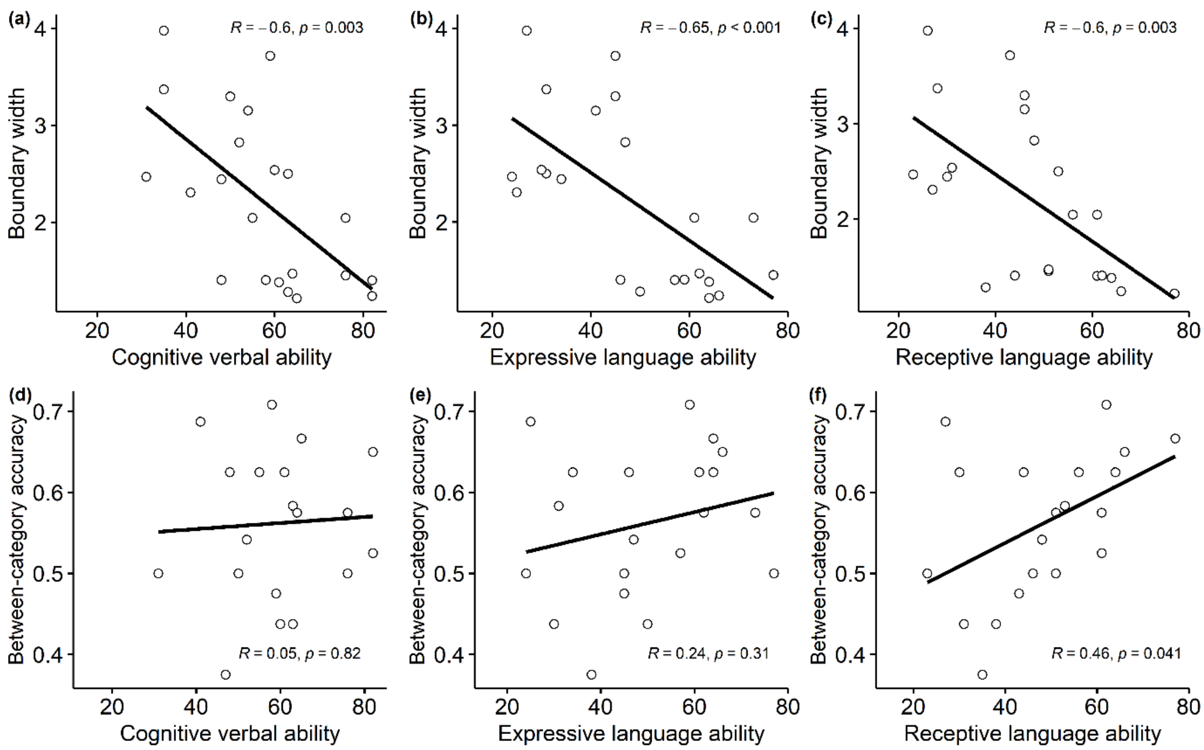

Figure 3. Correlation between boundary width and cognitive verbal ability (a), expressive language ability (b), and receptive language ability (c), respectively. Correlation between between-category discrimination accuracy and cognitive verbal ability (d), expressive language ability (e), and receptive language ability (f), respectively.

4. Discussion

The current study investigated Mandarin tone perception by examining the identification and discrimination of Tones 1 and 2 among language-delayed autistic children, and by comparing their level of CP ability with that exhibited among children in two non-autistic groups: one was matched for chronological age, and the other was matched for developmental age in language ability. Overall, the language-delayed autistic children exhibited a much wider boundary width than their chronological-age-matched non-autistic peers, while the boundary width of the autistic children was similar to that of the children in the developmental-age-matched non-autistic group. Furthermore, the language-delayed autistic children were less accurate than their chronological-age-matched non-autistic peers at discriminating between-category pairs, while they exhibited seemingly comparable discrimination accuracy to the developmental-age-matched but younger non-autistic children. While both non-autistic groups displayed an enhanced sensitivity to between-category tone pairs relative to within-category ones, such a CP feature was not observed among those in the autistic group.

4.1 Delayed CP development in autistic children and related factors

What contributes to the reduced degree of CP in autistic children compared to children in the chronological-age-matched non-autistic group? Weakened speech processing has also been widely observed by previous studies in tone-language-speaking autistic individuals (Jiang et al., 2015; Lau et al., 2021; Wang et al., 2017; Yu et al., 2015; Zhang et al., 2019). The inferior CP performance among autistic participants, in these previous studies, has mainly been attributed to their atypical focus on local details, and their reduced likelihood of integrating local details and processing them holistically (Frith, 1989; Mottron & Burack, 2001). To perceive Mandarin lexical tones, both low-level acoustic information and phonological information need to be processed and integrated simultaneously, but autistic individuals, who are less likely to integrate the information at two levels, will encounter difficulties with lexical tone perception. Another reason for the lower CP performance in autistic children than that among their chronological-age-matched non-autistic peers may be due to autistic children's lower language abilities. Language functions have been found to influence speech processing in both non-autistic (Kuhl et al., 2005, 2008; Rivera-Gaxiola et al., 2005; Tsao et al., 2004) and autistic individuals (Bishop et al., 2004; Chen & Peng, 2021; Constantino et al., 2007; Stewart et al., 2018). For example, autistic individuals with better language ability tend to show a narrower boundary width. Therefore, it is not surprising to find that language-delayed autistic participants in the present study performed worse on CP tasks than their chronological-age-matched non-autistic peers.

While autistic children performed worse on the CP tasks in comparison to the chronologically matched non-autistic group, they exhibited comparable boundary width and discrimination accuracy to the developmental-age-matched (but younger) non-autistic children. These results largely support the hypothesis of Chen and Peng (2021), who suggested that autistic children would show delay rather than impairment in their development of CP ability. These delays in autistic individuals have been mainly attributed to their poor language experience, because speech input has been considered essential for statistical learning of tonal variations and CP of native phonological contrasts (Best & McRoberts, 2003; Kuhl, 2004; Maye et al., 2002). Autistic children, whose low joint attention ability constrains language input, have less experience of language exchange than their chronologically matched non-autistic peers (Naigles, 2013), giving rise to relatively poor CP performance. The language experience of autistic children is believed to be closer to that of younger non-autistic children. This helps to explain the similar boundary width and discrimination accuracy observed between the autistic participants and the younger participants without autism. The finding that autistic participants had wider boundary width and lower discrimination accuracy than chronological-age-matched non-autistic participants, while these two aspects of CP degree in autistic participants were similar to those demonstrated by non-autistic participants matched on developmental age in language ability, indicates that basic language ability plays a role in the CP development of autistic children.

The role of language ability in autistic children's CP development was also supported by the results of regression analyses on the relationships between autistic children's language abilities and their degree of CP. The regression analyses indicated that language abilities (as measured via the three subtests on communication) predicted the degree of CP. Specifically, autistic children who had better receptive language ability, expressive language ability, and cognitive verbal ability demonstrated a narrower boundary width. In addition, as receptive language ability increased, the discrimination accuracy for between-category tone pairs increased. The ability to discriminate between-category pairs may rely more upon the ability to process received information, which is associated with receptive language ability. Boundary width, reflecting the capability to map ambiguous sounds into a certain category, may be linked to a broader aspect of language ability. The correlation between language ability and degree of CP was also seen in another subgroup on the autistic spectrum: autistic adolescents with better language capacity (Chen & Peng, 2021). These findings suggest that reduced CP competence of lexical tones observed in our autistic participants may be related to their difficulties with some aspects of language.

4.2 Absence of enhanced sensitivity to between-category lexical tone pairs in autistic children

In the discrimination test, the enhanced sensitivity to between-category tone pairs relative to within-category ones was observed in both non-autistic groups, but not in the autistic group. That is, non-autistic participants as young as four years old were observed to have developed the perceptual ability to process lexical tones as different categories, and their lexical tone perception was categorical, supporting previous findings by Chen et al. (2017) and Ma et al. (2021), who explored CP development in Mandarin-speaking non-autistic children. However, sensitivity to between-category tone discrimination was not elevated for the language-delayed autistic children. Although no significant difference was found between autistic children and developmental-age-matched younger non-autistic children in between- and within-category discrimination accuracy, a significantly higher discrimination accuracy for between-category tone pairs than within-category ones was only observed in the non-autistic group. The absence of difference between autistic and non-autistic groups might be attributed to between-subjects comparisons, where it is relatively difficult for group difference to reach significance, while the enhanced sensitivity to between-category tone pairs was measured on the basis of within-subject comparisons. The results of within-subject comparisons further suggest that individual subjects in the non-autistic group were relatively consistent in performing better at discriminating between-category tone pairs than within-category ones. However, this consistency is lower in the autistic group, with a number of participants in the autistic group not achieving higher accuracy in between-category pairs than within-category ones. The lower consistency in the autistic group may be accounted for by their larger variation in developmental age in language ability. Although the developmental age of both autistic and younger non-autistic children was around four (i.e., 4.37 and 4.36), the standard deviation varied considerably in the autistic group (1.12 vs. 0.66). From the finding of a CP pattern (i.e., an enhanced sensitivity to between-category tone pairs) in non-autistic children around four years of age (Chen et al., 2017; Ma et al., 2021), it can be inferred that the key turning point is language ability at around four years old. The larger standard deviation of language ability in the autistic group suggests more autistic children's developmental age fell far below the key turning point, which might contribute to the absence of CP pattern in this group. Therefore, we expected a preserved CP pattern to be found in autistic participants with higher developmental age. To test this hypothesis, we divided autistic participants into two subgroups based on a median split on their developmental age. We found a significantly higher discrimination accuracy for between-category tone pairs than for within-category ones in an autistic subgroup with a developmental age of 5.29 but not in the other subgroup with younger developmental age (see Supplementary Materials 4). The finding of a clear CP pattern in non-autistic children aged around four, together with the finding that the CP pattern was observed among autistic children with developmental age around five instead of four, indicated that autistic children seemed to require the extended development to achieve an equivalent CP ability in comparison to non-autistic children.

Additionally, in the discrimination test, the language-delayed autistic children did not display a higher discrimination accuracy for within-category tone pairs relative to the non-autistic children. The results of the present study seem to contradict previous studies showing enhanced local pitch discrimination ability among autistic individuals (e.g., Bonnel et al., 2003, 2010; Järvinen-Pasley & Heaton, 2007; Lepistö et al., 2005; Mayer et al., 2016). We speculate that one possible explanation for this inconsistency is that the autistic groups in the previous studies differed from the current one's. For instance, in Bonnel et al. (2010) and Mayer et al. (2016), participants were adolescents and adults, and Bonnel et al. (2003) focused on autistic savants. Another possible reason for the contrast is that the stimuli used in the current study were linguistic, whereas those employed in previous studies focused on non-linguistic pitch (e.g., pure tones, musical notes, etc.). Our results suggest that autistic children would not show an enhancement in processing linguistically-relevant pitch patterns, which was also detected in other types of linguistic sound stimuli, such as the processing of Cantonese monosyllabic word /ji/ with three different tone levels by autistic children and adults (Lau et al., 2021) and the perception of a Mandarin lexical tone continuum (word /ba/ with Tones 1 to 2) by autistic adolescents (Chen & Peng, 2021). In previous studies using non-linguistic stimuli, autistic participants showed enhanced perceptual ability, whereas no superior perception of lexical tones was observed by the current study, providing further evidence for a domain-specific deficit in pitch processing associated with autism (Yu et al., 2015). That is, autistic individuals were found to exhibit better CP performance during a behavioural experiment (Chen & Peng, 2021) and enhanced MMN effect during an electrophysiological investigation (Yu et al., 2015) when processing non-linguistic stimuli, while linguistic-related ones would give rise to opposite findings.

4.3 Limitations and future directions

This study presents several limitations that deserve attention. First, while here we focused on language-delayed autistic children whose developmental age in language ability was around four years old, the current findings do not necessarily extend to other subgroups of autistic individuals. Language ability has been found to play a role in the development of CP. Thus, future studies with autistic and non-autistic children matched on both chronological age and language ability would allow uncovering CP development more comprehensively in autistic children. Second, CP can be impacted by a variety of factors that would require more careful monitoring in future work so as to tease their role apart from that of language ability and chronological age. For instance, more precise data on the participants' cognitive abilities, like executive function, could yield additional insights into children's CP performance. Executive function is a set of abilities that control cognitive processes, such as working memory and inhibition. Some scholars have argued that the discrimination task of judging two sounds as the same or different involves working memory (Xu et al., 2006). To judge correctly, one prerequisite is to store the first sound and compare it with the second one (Mitterer & Mattys, 2017). Feng et al. (2021) found that cognitive load negatively affected pitch sensitivity and discrimination performance by interfering with working memory in non-autistic individuals. Future studies examining working memory are warranted to uncover the factors in the CP of autistic children. Additionally, inhibition has been believed to be essential for suppressing the detection of within-category differences (Yu et al., 2015). Given this, a measure of inhibition would be an important addition to future work exploring CP. Third, the information on the autistic participants' language functions collected here could not reveal a full profile of the participants. In light of the huge heterogeneity in general cognitive functions within the autistic spectrum, a formal test of nonverbal intelligence quotient should be applied in future CP investigations in autism.

5. Conclusion

The present study investigated the CP of lexical tones in language-delayed autistic children from a tone language background. Results suggest these autistic children's development of CP of Mandarin tones is delayed, and they seem to require extended development to achieve the typical CP pattern of lexical tones in comparison with non-autistic children. The findings of the current study improve our understanding of phonological processing in a subgroup of tone-language-speaking autistic children. In addition, the development of CP was found to correlate with language ability, indicating that poor CP of speech sounds can be predictive of autistic children's language disability.

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