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Developmental trajectories of non-native tone perception differ between monolingual and bilingual infants learning a pitch accent language

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ABSTRACT

The developmental trajectories of tone perception among tone and non-tone language learning infants have received wide attention and discussion in recent decades under the perceptual attunement framework. Nevertheless, tone perception in infants from pitch accent and bilingual language backgrounds has not been well understood. The present study examined monolingual and bilingual Norwegian-learning infants' discrimination of two Cantonese tone contrasts at 5 and 10 months, ages corresponding to the onset and offset of perceptual attunement. Results showed that while monolingual infants were sensitive to the salient contrast, bilingual infants showed sensitivity to both contrasts at 10 months. In sum, infant age and bilingual language background affected discrimination. Pitch accent language experience or contrast salience may also play a role. The finding that early bilingual experience facilitated tone perception is of particular interest. It suggests that infant perception could be enhanced by a more complex linguistic environment on a broader level. As this was observed only at 10 months, cumulative exposure may be required for infants in a complex bilingual environment. Future studies should disambiguate explanations generated from the current finding, ranging from neurocognitive plasticity to perceptual salience, and from experience-dependent to independent possibilities.

1. Introduction

More than 70 % of the world's languages are tone languages which use pitch variations (e.g., pitch height and contour, Liu & Samuel, 2004) to distinguish word meanings (Yip, 2002). In tone perception, listeners' discrimination ability has been predominantly

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associated with language experience as they grow, evidenced by perceptual development and differences between infants learning tone languages (e.g., Cantonese, Fig. 1 left) versus non-tone languages (e.g., French). The current study examined infants learning a pitch accent language under the perceptual attunement framework established by Werker and Tees (1984). We choose to use the term perceptual attunement instead of perceptual reorganization to place emphasis on input dependency and developmental trajectories. Exploring perceptual attunement in a pitch accent language allowed us to tease apart the key question of the extent to which young learners' experience with a specific linguistic feature would facilitate the perception of different representations of the same feature in a new language.

Within the perceptual attunement framework (Werker, 2024), three key variables were examined in this study: infant age, language background, and tone contrast salience. Studying perception at different ages would reveal developmental changes. Assessing monolingual and bilingual infants would tease apart specific (e.g., lexical pitch use) and general (e.g., complex language environment) impacts. Adopting tone contrasts that differ in salience would allow assessment of the level of stimuli-induced impact. Being able to interpret the role of these factors in a pitch accent language makes a valuable contribution to existing developmental and perceptual theories.

1.1. The developmental trajectory of lexical tone perception

Language experience modulates speech perception. In the first year after birth, infants shift their attention from a wide range of speech contrasts to focus on contrasts within their native languages (Werker & Tees, 1984). This process has been argued to be domain-general and related to changes in neural plasticity (Werker & Hensch, 2015; Werker & Tees, 2005), termed neural commitment (Kuhl et al., 2008) with biological underpinnings (Reh et al., 2020). While sensitivity to pitch is evident since birth (Nazzi et al., 1998), tone language-learning infants must learn that specific pitch contours are phonologically contrastive just like other phonological contrasts. This is shown in maintenance and/or improvement patterns in their tone perception across ages (Harrison, 2000; Singh et al., 2018; Tsao, 2017; Yeung et al., 2013). Meanwhile, non-tone language-learning infants must learn to disregard pitch variation as lexically non-informative. Their tone discrimination has often been reported to follow a pattern of deterioration or attenuation in the first year of life (Cabrera et al., 2015; Mattock & Burnham, 2006; Mattock et al., 2008; Shi et al., 2017). The perceptual differences between tone and non-tone language speakers extend to adulthood (Hallé et al., 2004), reflecting a language-specific influence on tone perception.

Meanwhile, mixed findings, inconsistent with canonical perceptual attunement patterns along the development of lexical tone perception have been reported in both tone and non-tone language-learning populations, reflecting a rather complex picture. On the one hand, some tone language-learning infants exhibit levels of perceptual difficulty and varying paces of learning trajectories with different tones (Singh et al., 2018; Tsao, 2008; 2017). On the other hand, non-tone language-learning infants show robust discrimination for some tone contrasts across ages (Chen & Kager, 2016; Chen et al., 2017). These patterns have been replicated in a recent collaboration across 13 laboratories examining tone perception among infants across ages and language backgrounds (Kalashnikova et al., 2024). Further, a U-shaped perceptual pattern has been reported among non-tone language-learning infants, consisting of a dip

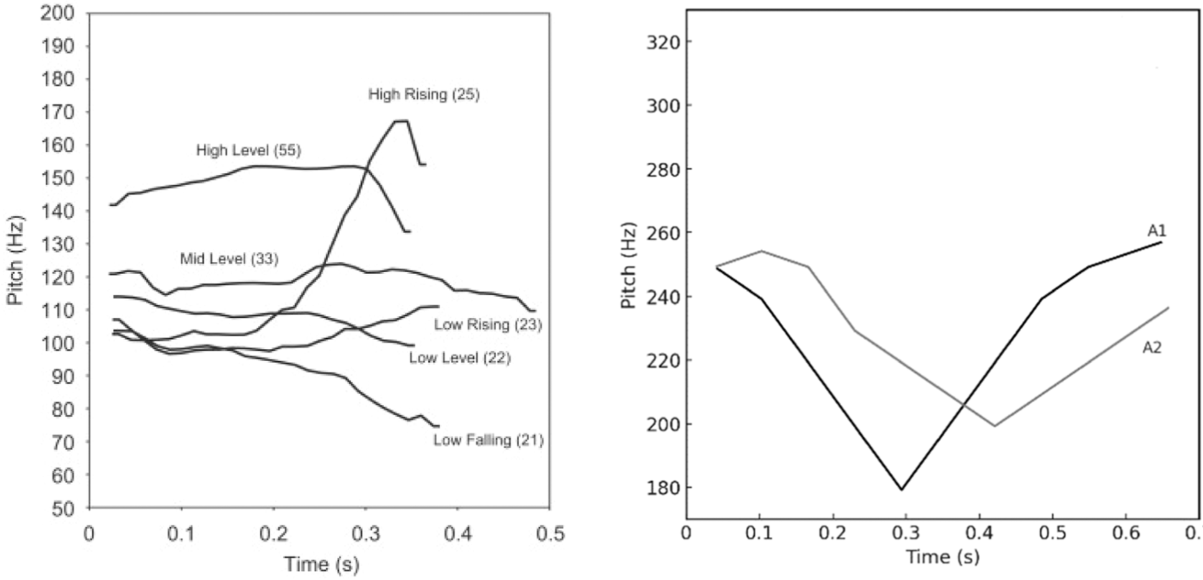


Fig. 1. Illustrations of Cantonese tones (left) and Oslo Norwegian pitch accents (right).
Note: Cantonese source from Francis et al. (2008) based on single-syllable words; Norwegian source adapted from Kristoffersen (2006; A1 = Accent 1; A2 = Accent 2) based on two-syllable words. The x-axis represents time in seconds (left) or milliseconds (right). The y-axis represents pitch or fundamental frequency (F0) in Hz. Pitch directions are simple for Cantonese tones, but complex for Norwegian pitch accents.

in tonal sensitivity at the end of the first year followed by a resurgence in the second year (Götz et al., 2018; Liu & Kager, 2014). The later recovery has been argued to resemble infants' overall auditory pitch sensitivity without phonological knowledge, given the findings that infants' ability to associate non-native tones with labels deteriorates in the second year (Hay et al., 2015; Hay et al., 2019; Liu & Kager, 2018; Singh et al., 2014). As these mixed findings call for more studies, the current study fills the gap by pioneering tone perception assessment of monolingual and bilingual pitch accent language-learning infants across ages.

1.2. The case of pitch accent languages

Most prior studies focus on tone perception between tone and non-tone language learners and speakers. Much less attention has been paid to the extent to which pitch accent language experience affects tone perception in infancy. Like in tone languages, pitch conveys lexical information in pitch accent languages (e.g., Norwegian, Fig. 1 right) in which accentuated syllables can be marked by contrasting pitch patterns (Kubozono, 2012). In other words, comprehension of these minimal word pairs in pitch accent languages requires decoding lexical pitch information just like in tone languages. However, unlike tone languages, minimal pairs that are contrastive in pitch typically apply only to a limited subset of two-syllable words in a pitch accent language, whereas the much larger rest of the pitch accent language inventory follows stress language rules.

The classification of pitch accent languages complicates matters further, as they may consist of not only one, but two cues, lexical pitch and stress accent, within the same syllable. For instance, Hyman, (2006; 2009) classifies languages according to whether a language has tone (e.g., Yoruba), stress accent (e.g., English), both (e.g., Serbo-Croatian) or neither (e.g., Bengali). Note that this is not an issue specific to pitch accent languages, as all languages adopt diverse cues in phonology. In tone languages, tones are predominantly realized by two cues, pitch height and pitch direction (Liu & Samuel, 2004). It is unclear how listeners from a tone language perceive the other cue when only one cue is used in that language. As a pitch accent language, Norwegian differs from tone or non-tone languages in its pitch use (Hyman, 2006; 2009). It is also not yet represented among international perceptual narrowing studies (Singh et al., 2022). The tonal patterns in Norwegian are less complex than those in tone languages, which typically employ more featural distinctions and a wider range of tonal variations, such as those comprising over two tones. Additionally, accent patterns exist across many Norwegian words, but are only contrastive on the basis of pitch for minimal pairs.

1.3. The case of bilingualism

The extent to which bilingualism affects speech perception in infancy and early childhood remains a topic of debate. Some have shown that bilingual language experience can lead to enhanced speech processing (Petitto et al., 2012) and non-speech perception (Liu & Kager, 2017a) in infancy. Compared to monolinguals, bilingual infants exhibit a sensitivity recovery to non-native tones six months earlier (Liu & Kager, 2017b), and show less neural commitment, that is more plastic establishment of neural pathways (Kuhl et al., 2008).

Meanwhile, other findings suggest that early bilingualism does not always affect speech perception. Some argue that monolingual and bilingual infants pass through major linguistic milestones approximately at the same points in their developmental timelines (Werker, 2012), consistent with findings reporting an equal pace of the perceptibility of speech contrasts among infants across language backgrounds (Kalashnikova et al., 2024). Some have reported a temporary delay for bilingual infants when discriminating some speech contrasts (e.g., Garcia-Sierra et al., 2011). For instance, a temporary delay has been reported for Catalan /e/-/ɛ/ contrast among Catalan-Spanish bilingual infants when compared to their monolingual peers (Bosch & Sebastián-Gallés, 2003), although this finding failed to replicate in a follow-up study (Albareda-Castellot et al., 2011). Others have shown a lack of discrimination among bilingual infants for native languages (Bosch & Sebastián-Gallés, 1997), consonants (Bosch & Sebastián-Gallés, 2003; Garcia-Sierra et al., 2011), vowels (Bosch & Sebastián-Gallés, 2001; Sebastián-Gallés & Bosch, 2009), tones (Singh & Foong, 2012), and non-native contrasts (Havy et al., 2016; Sebastián-Gallés & Bosch, 2009).

It is unclear to what extent the observed discrepancies between monolingual and bilingual infants may be attributed to their overall and specific language experiences. On a general note, the presence of two languages has been argued to lead to more plasticity in processing on both neural (Petitto et al., 2012) and cognitive levels (Curtin et al., 2011). At the same time, bilingual infants are likely to experience reduced language input per language compared to their monolingual peers. As the process of neural commitment relies upon language input quantity and quality, which further influences category robustness (Garcia-Sierra et al., 2016; Marklund et al., 2019; Pallier et al., 1997), reduced input may imply more flexible or lengthened category formation. More specifically, a speech unit or feature may occupy different functions in the languages bilinguals acquire, leading to distinct opportunities and challenges along the attunement trajectory. Bilingual infants learning English and Mandarin did not discriminate either salient or non-salient lexical tone contrasts throughout the first year after birth (Singh et al., 2018), suggesting interferences of language-identifying or contextual cues required for bilinguals to differentiate pitch variation in a language-specific manner (Singh & Foong, 2012).

1.4. Contrast type and salience

With tone contrasts of different salience, discrimination outcomes differ across listeners as a function of language background as well as age, ranging from infancy (Burnham & Singh, 2018; Singh & Fu, 2016) to adulthood (Burnham et al., 2014; Huang & Johnson, 2011). Some have attributed such differences to salience, defined as the conspicuity of a stimulus relative to its surrounding items (Günther et al., 2017). Salience can be acoustic. Some have suggested that contour tones may be more salient than level tones (Mattock & Burnham, 2006). Others have reported that more dynamic tones, that is, tones with more complex directions (Abramson, 1978) may be more salient than less dynamic tones (Liu et al., 2022). Salience can also be experience-based and therefore learned. Non-native tones that may be assimilated into one's native language can be more easily perceived (Hay et al., 2019), aligning with perceptual assimilation theories (Best, 2019; Tyler et al., 2014). For example, a rising tone may be assimilated to and perceived as interrogative intonation by English listeners (Kaan et al., 2008; So & Best, 2014).

It is not surprising that findings on how salience affects tone perception are mixed. Some studies report a progressive developmental trend. English-learning infants do not discriminate either salient or non-salient Mandarin tone contrasts at 6 months but can do so at 12 months (Singh et al., 2018). Some have found perceptual maintenance from 5- to 18-month-old infants learning tone or non-tone languages in salient (Cabrera et al., 2015; Liu & Kager, 2014; 2017a) as well as in non-salient tone contrasts (Ramachers et al., 2018; Shi et al., 2017; Tsao, 2008). Others have not observed sensitivity even for tone contrasts that are deemed salient (Tsao, 2017). Albeit the consensus is that salience contributes to diverse outcomes in tone perception, the specific properties that qualify a tone or a tone contrast as salient or non-salient remain unclear.

1.5. *The present study*

While studies emerge on the developmental trajectory of tone perception, much less attention has been paid to pitch accent language learners as well as to infants with diverse language experiences. It is of interest to study perceptual attunement in infants who learn a language with only a portion of its inventory defined by lexical pitch and those who grow up with more than one language. In the current study, monolingual and bilingual Norwegian-learning infants' perception of two non-native Cantonese tone contrasts was examined cross-sectionally at 5 and 10 months via a habituation paradigm. Selecting infants learning a pitch accent language and the use of tone contrasts with varying acoustic salience takes factors such as amount of exposure or the acoustic properties of lexical tones into play. These factors might influence tone perception development, even in infants learning non-tonal languages. This implies that language-general mechanisms, such as statistical learning or sensitivity to acoustic salience, could play a role in the development of tone perception in preverbal infants. Given the design, a preference for novel over habituated stimuli was expected should infants discriminate the target contrast. This was marked as the variable Trial Type in the study.

The current study explored the effects of the variables Infant Age (5 months, 10 months), Language Background (monolingual, bilingual), and Tone Contrast (less salient, more salient) in Norwegian-learning infants' tone discrimination. The predictions were: 1. Infant Age: Following the perceptual attunement account (e.g., Werker & Tees, 1984; Werker, 2024), 5-month-olds were expected to exceed 10-month-olds in non-native tone perception. 2. Language Background: Given the pitch use in a pitch accent language like Norwegian, monolingual and bilingual infants may both be sensitive to tones despite that these are non-native to them. We left it open whether to expect differences in perceptual patterns between monolingual and bilingual infants or not. 3. Tone Contrast: More salient contrasts would be better discriminated than less salient contrasts.

2. Method

2.1. *Participants*

Data from 64 (N_{female}=33) typically developing Norwegian-learning infants were incorporated into the final analysis, with each group of the variables Infant Age (5 months vs. 10 months) and Language Background (monolingual vs. bilingual) consisted of 16 infants (Table 1). This sample size adheres to the suggested number in infant looking-time research (Oakes, 2017). It fits the a priori power analysis required to test the study hypothesis using G*Power version 3.1.9.7 (Faul et al., 2007) to achieve 80 % power for detecting a small-to-medium effect ($f = 0.18$) at a significance criterion of $\alpha = .05$ using repeated measures analysis of variance (RM ANOVA). Infants were from families of comparable socioeconomic backgrounds, as socioeconomic status may affect phoneme discrimination (Singh et al., 2023). Norwegian refers here to families who speak a Norwegian dialect that employs pitch accent contrastively. Bilingual infants had Norwegian as one of their native languages, while their other language varied (Appendix A), but did not include tone or other pitch accent languages. The degree of exposure to the other language was no less than 25 % of the total exposure as assessed via the Multilingual Infant Language Questionnaire (Liu & Kager, 2017c). The mean and standard deviation of the degree of exposure to Norwegian in bilingual infants was 50 % and 16 %, respectively. Data from eleven additional infants were excluded due to infants being exposed to a tone or another pitch accent language (N=9), less than 25 % exposure to Norwegian (N=1), and failure to habituate after 25 trials in the habituation phase (N=1). The Norwegian Centre for Research Data (NSD) approved the study (Ethics approval number 827317).

Table 1
Descriptive statistics of participants across language background and infant age (in days).

Age Group	Background	Number	Number (Female)	Mean age	SD age
5 months	Monolingual	16	7	158	13
	Bilingual	16	8	164	12
10 months	Monolingual	16	7	299	19
	Bilingual	16	8	300	18

2.2. Stimuli

For auditory stimuli, three Cantonese tones, rising (25), mid-level (33), and falling (21) were used. The inclusion of static and dynamic tones in the contrasts follows prior studies that suggest that pitch contours are relevant to tone sensitivity (Burnham, Singh, Mattock, et al., 2018). Listeners categorise tone 25 as rising and tone 33 as clear flat (Francis et al., 2008). Though named falling, tone 21 was categorised as low by non-Cantonese speakers (Kalashnikova et al., 2024). These three tones formed two contrasts in the current study. The 25–33 contrast was considered relatively more salient and the 25–21 contrast was less salient. A female native Cantonese speaker from Hong Kong produced multiple tokens of these tones in live, infant-directed speech with /lIn/ as the carrier, among which four tokens of each tone were selected (see Appendix B for detailed acoustic characteristics). Crucially, none of these pitch contours matched the Norwegian pitch accent patterns as both involve dipping. For each tone, its corresponding tokens were concatenated into 20-s strings with 14 tokens and an inter-stimulus interval of around 900 ms per string. The strings of tone 25 were used in the habituation and the re-familiarisation phases, as well as the habituated trials in the first-test and the second-test phases. Further, tokens of 25–33 and 25–21 were alternatingly concatenated into perceptually more and less salient trials, respectively as the new trials in the first-test and the second-test phases. Each tone string consisted of a 20-second (14 tokens) audio display of tokens. The falling tone string was set as the stimuli string in habituation, habituated test, and re-familiarisation trials. The novel test trials were falling-rising (salient) or falling-level tones, and whether the first trial was novel or familiar was counterbalanced across infants. Additionally, the syllable /paːk/ was repeated in the pre-test and post-test trials to ensure the attention was kept throughout the experiment, and a musical string was played along with the attention-getter. Auditory stimuli volume was kept at 65 dB.

As visual stimuli, a static colourful bullseye was used across all trials. The bullseye retracted and expanded in between these trials, functioning as attention-getter. A video of a moving waterwheel toy presented on a black background was used in the pre-test and post-test trials.

2.3. Procedure

Participating families were recruited from a sign-up list the Social and Cognitive Lab at the University of Oslo. Upon visiting the lab, caretakers provided the demographic backgrounds of their children such as age, gender, and language experience. The experimental procedure was adapted from an existing infant gaze-controlled alternating stimulus paradigm (Tyler et al., 2014), allowing for within-subject measures of two contrasts in a single experiment. The duration of all trials was between 1 and 20 seconds as a function of infant gaze. Each trial began after infants fixated the attention-getter at the centre of the screen. A trial ended when infants looked away for more than 1 second.

The paradigm consisted of six blocks presented in chronological order: pre-test, habituation, first-test, re-familiarisation, second-test, and post-test. The pre-test and post-test blocks measured general attention at the beginning and at the end of the experiment. This ensured that a failure to discriminate was not due to attentional, but perceptual reasons. The habituation phase was concluded when infants reached the habituation criterion of a mean 50 % decrease in looking time (LT) in three consecutive trials compared to the baseline - which was calculated as the average LT in the first three trials -, or when a maximum of 24 trials was reached. The first-test block consisted of two trials, one old, habituated trial in which repetitions of the habituated stimulus were presented, and one new, alternating trial in which the habituated stimulus and a novel stimulus were presented in alternation. Significant differences between habituated and new trials indicate discrimination. The re-familiarisation block consisted of three trials to reinstate the habituated stimulus as baseline before the start of the second-test phase. The second-test block had the same format as the first-test block, and the new, alternating tone presented in the test phase was counterbalanced between blocks. For example, if the perceptually more salient /25–33/ tone contrast was presented in the first-test block, then the less salient /25–21/ was presented in the second-test block.

During the experiment, infants sat on their caretaker's lap in the test booth, facing the experimental display. No visual or auditory distractions were present in front of the infants. Caregivers wore headphones to block auditory stimuli (Nelson et al., 1995) and were instructed to not speak to their infant or point to the screen. An experimenter observed the infants through a closed-circuit TV in a room adjacent to the test booth and conducted online coding of infant looking time towards the screen. Infant looking time (in milliseconds) in the test phase was put to analysis.

3. Results

Data were analysed using repeated measures ANOVA (SPSS version 22.0, IBM Corp., 2013). The between-subject variables

Table 2
Descriptive statistics of infant looking time across infant age, language background, tone contrast, and trial type.

Infant Age	Language Background	Tone Contrast: less salient		Tone Contrast: more salient	
		Habituated	New	Habituated	New
5 months	Monolingual	4870 (820)	4513 (786)	4214 (641)	6283 (972)
	Bilingual	4216 (588)	3815 (751)	4353 (621)	3857 (560)
10 months	Monolingual	4006 (515)	3585 (624)	4172 (588)	4563 (858)
	Bilingual	3592 (592)	6680 (1293)	3412 (518)	4006 (515)

Note: Numbers indicate Mean (SE) looking time in milliseconds. See Appendix C for corresponding figures.

included Infant Age (5 months/10 months) and Language Background (monolingual/bilingual), whereas the within-subject variables were Tone Contrast (more salient/less salient), and Trial Type (habituated/new). Descriptive results across the four variables are presented in Table 2.

Results revealed two interaction effects. First, a significant interaction was observed between Infant Age, Language Background, and Trial Type ($F(1, 60) = 5.29$, $p = .02$, $\eta_p^2 = .08$; Fig. 2). Post-hoc analyses comparing Infant Age across Language Background and Trial Type revealed no significant difference between 5- and 10-month-olds (largest $\beta = 1507.22$, SE = 852.96, $p = .08$, $\eta_p^2 = .05$). Likewise, when comparing Language Background across Infant Age and Trial Type, no significant difference was observed between monolingual and bilingual infants (largest $\beta = 1562.25$, SE = 852.96, $p = .07$, $\eta_p^2 = .05$). When comparing habituated and new trials, the observed significance was present in 10-month-old bilinguals ($\beta = 1841.25$, SE = 687.05, $p = .01$, $\eta_p^2 = .11$) but not in 5-month-olds nor in monolingual infants (largest $\beta = 856.09$, SE = 687.05, $p = .22$, $\eta_p^2 = .03$). In other words, bilingual infants at 10 months of age were more sensitive to the new than to the habituated trials, indicating discrimination of both tone contrasts.

Second, the other significant interaction was observed among Language Background, Tone Contrast, and Trial Type ($F(1, 60) = 4.80$, $p = .03$, $\eta_p^2 = .07$, Fig. 3). Post-hoc analyses comparing Language Background across Tone Contrast and Trial Type revealed a difference between monolingual and bilingual infants' looking time towards the new trial of the salient contrast ($\beta = 1491.84$, SE = 751.72, $p = .05$, $\eta_p^2 = .06$). Particularly, monolinguals looked longer than bilinguals at this trial. Likewise, when comparing habituated and new trials across Language Background and Tone Contrast, monolingual infants discriminated the more salient contrast ($\beta = 1230.13$, SE = 586.10, $p = .04$, $\eta_p^2 = .07$), whereas bilingual infants or the less salient contrast did not yield a difference (largest $\beta = 1343.69$, SE = 755.36, $p = .08$, $\eta_p^2 = .05$). When comparing Tone Contrast across Language Background and Trial Type, no significant difference was observed (largest $\beta = 1374.13$, SE = 805.33, $p = .09$, $\eta_p^2 = .05$).

4. Discussion

The current study examined tone discrimination between habituated and new tone contrasts among pitch accent language-learning infants focusing on infant age (5 months vs. 10 months), language background (monolingual vs. bilingual), and contrast salience (/25–33/ vs. /25–21/). Although these factors were not significant standing alone, two patterns predictive of infants' perceptual outcomes emerge from their interactions. First, monolingual Norwegian-learning infants showed discrimination of the more salient tone contrast by looking longer at the new trial than their bilingual peers. Second, bilingual infants discriminated both tone contrasts at 10 months.

Monolingual Norwegian-learning infants' sensitivity towards the salient contrast conforms to previous findings. Both Dutch-learning (non-tone) and Limburgian-learning (pitch accent) infants were sensitive to Limburgian pitch accent contrasts at 6 and 12 months (Ramachers et al., 2018). Moreover, both tone and non-tone language-learning infants could distinguish non-native tone contrasts at 6 months (Kalashnikova et al., 2024). Although analyses showed that age was not a significant factor among the monolinguals, Table 2 suggested that discrimination appears to be more evident at 5 than 10 months, consistent with established patterns of perceptual attunement (Kuhl et al., 2008; Werker & Tees, 1984). Having said that, the nature of such discrimination remains unclear. Since monolingual Norwegian-learning infants did not exhibit the same level of discrimination towards the less salient contrast, it is unclear whether the perceived sensitivity is due to contrast salience or infants' prior experience with a pitch accent language.

Following previous discussions (Fikkert et al., 2020; Sundara et al., 2008), contrast salience played a role in tone discrimination in the current study. We further hypothesise that a more salient contrast, such as a contrast reflecting pitch patterns (Liu et al., 2023; Sundara et al., 2018) or articulatory patterns (Qin & Zhang, 2022; Zhang et al., 2022) used in learners' native languages, may lead to

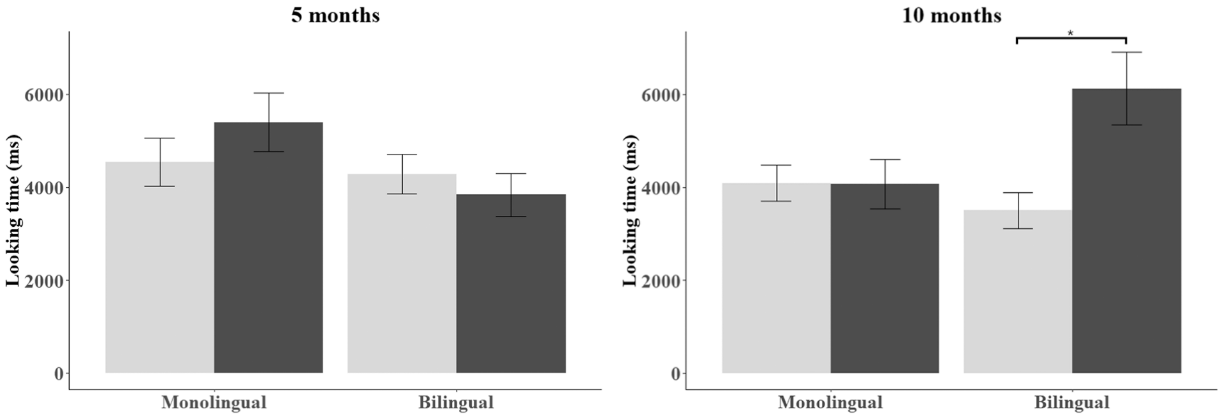


Fig. 2. *Norwegian infants' discrimination of Cantonese tones across infant age and language background.*
Note: Figures represent infant looking time at 5 (left) and 10 (right) months aggregated across two contrasts. The x-axis represents the participants' language background. The y-axis represents looking time towards the habituated (light colour) and new (dark colour) trials in the test block. Error bars = ±1 SE.

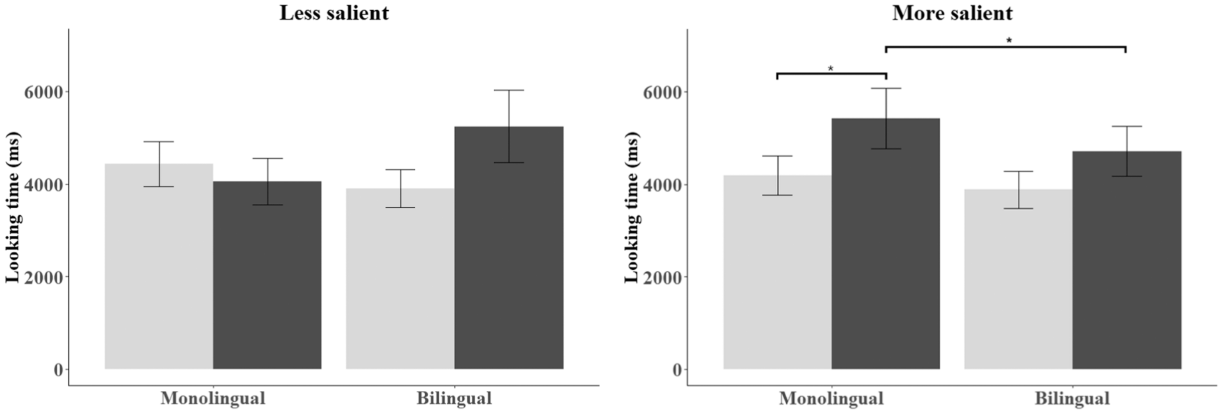


Fig. 3. *Norwegian infants' discrimination of Cantonese tones across tone contrast and language background.*
Note: Figures represent infant looking time towards the less salient (left) and more salient (right) contrast aggregated across two age groups. The x-axis represents participant language background. The y-axis represents infant looking time towards the habituated (light colour) and new (dark colour) trials in the test block. Error bars = ±1 SE.

better discrimination. Future studies can focus on the degree of assimilation between the non-native contrasts and the native pitch accents, taking the intonational (Best, 2019; Frota et al., 2014; Kager, 2018), emotional (Liu et al., 2022) and non-linguistic/musical (Chen & Liu, & Kager, 2016; Liu et al., 2017; Wong et al., 2007) functions of pitch into consideration.

Bilingual infants showed elevated perceptual sensitivity to both contrasts at 10, but not at 5 months. We hypothesise that effects of language learning in a bilingual environment may be cumulative, with more facilitation effects surfacing in the second half of the first year, echoing previous findings (Liu & Kager, 2015; Liu et al., 2019). For instance, Dutch-learning bilingual infants' sensitivity to a native /i/-/I/ vowel contrast increased from 5 to 9 months, whereas their monolingual peers did not exhibit the same level of sensitivity at either age (Liu & Kager, 2016). As the current study examined a non-native contrast, the observed improvement pattern among bilinguals appears to be language-general, applying to native and non-native domains.

As the non-Norwegian languages acquired in addition to Norwegian by the bilingual infants in this study were not tonal (e.g., English, German), different perceptual patterns arose between monolingual and bilingual infants. The observed sensitivity in bilinguals may be explained by learning from the intrinsic differences between the two languages when only one involves lexical pitch use, marking a linguistic distinction in this feature. Alternatively, bilingual facilitation may simply be attributed to a more complex environment with a greater number of phonemes and higher density in phonetic inventory. As a result, bilingual infants may be more cautious, taking their time to accurately acquire phonemic features in their more complex language environment, and displaying enhanced perceptual sensitivity not until the second half of the first year after birth. It is difficult to discern whether the observed enhancement at 10 months is due to bilingual infants' plasticity in linguistic sensitivity, perceptual sensitivity, or cognitive advantage. It is worth noting that although understanding and command of dual language systems may promote cognitive processing early on in life (Kovács & Mehler, 2009), the bilingual cognitive advantage is under heated discussion and debate (Arredondo et al., 2022; Baum & Titone, 2014; Bialystok, 1999; 2001; 2009; Valian, 2015).

4.1. *Limitations*

The observed findings do not reveal the definitive nature of perception in both monolingual and bilingual populations. Unlike in adult experiments where multiple tone contrasts can be extensively examined (e.g., Huang & Johnson, 2011), only one or two contrasts can be tested in infant experiments. This constraint makes it difficult to interpret the non-significant results in relation to contrast salience. Future studies are required to disentangle possible explanations, ranging from neurocognitive plasticity to perceptual salience and from experience-dependent possibilities to non-exposure related explanations. Outcomes of the current study may be a function of the experimental design (e.g., including both familiar and novel tokens in test phases) and the relatively small sample size for pairwise tests.

4.2. *Conclusion*

This study is the first to report on the extent to which monolingual and bilingual pitch accent language-learning infants discriminate non-native tone contrasts. While monolingual infants were sensitive to the more salient contrast, bilingual infants showed sensitivity to both contrasts at 10 months. These results showed that infant age and bilingual language background affected discrimination, while pitch accent language experience or contrast salience may also play a role. These results contribute to our understanding of perceptual attunement theories, highlighting the importance of variables like language background for the developmental trajectories of infant speech perception.

CRediT authorship contribution statement

Iris-Corinna Schwarz: Writing – review & editing, Conceptualization. **Lisa Gustavsson:** Writing – review & editing, Conceptualization. **Ellen Marklund:** Writing – review & editing, Conceptualization. **Liquan Liu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anne Marte Haug Olstad:** Writing – review & editing, Data curation.

Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A

Language Exposure in Addition to Norwegian

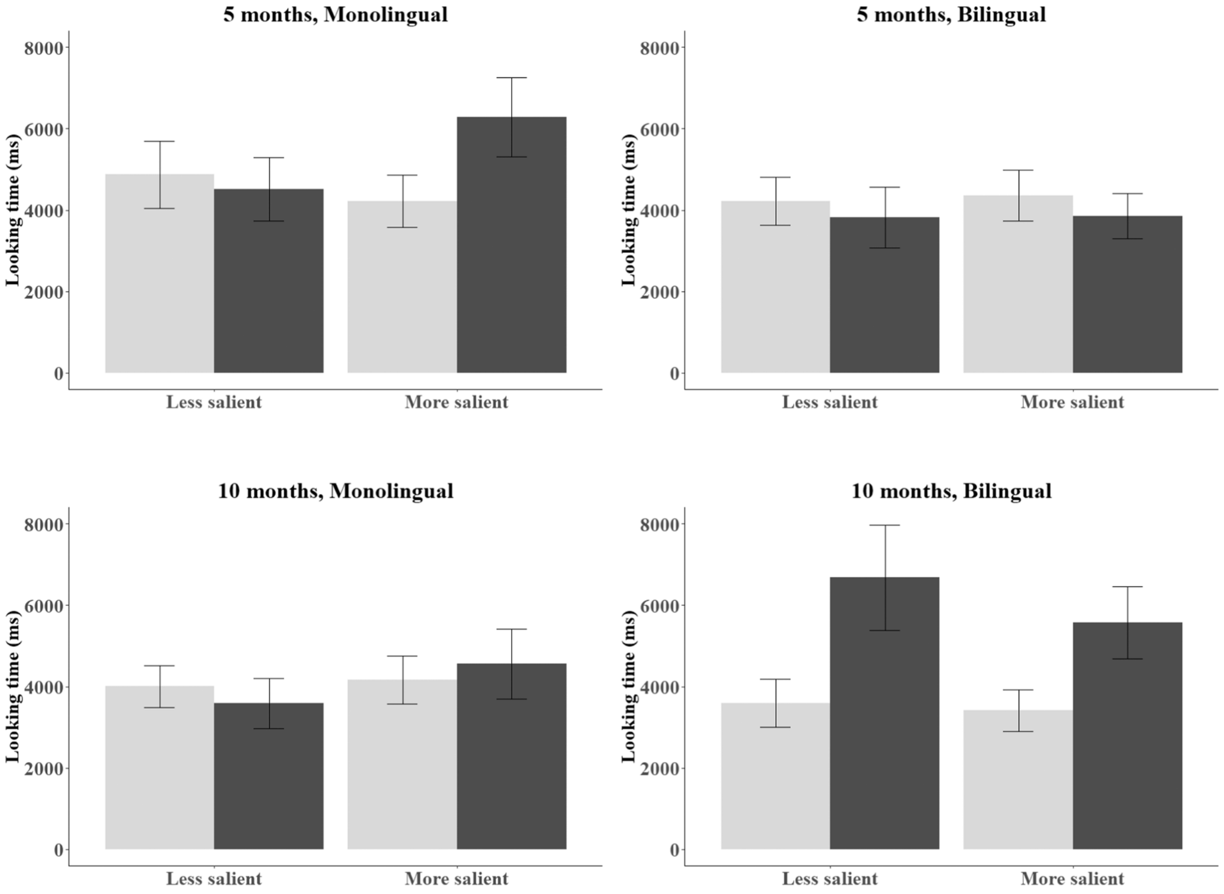
	5 months	10 months
Dutch		1
English	7	3
Finnish		1
French	1	1
German	3	3
Macedonia		1
Polish	3	
Russian		1
Spanish	2	3
Slovak		2
Total	16	16

Appendix B

Detailed acoustics of the tokens used in the experiment

	Token	Mean (Hz)	Onset (Hz)	Offset (Hz)	Duration (ms)
Tone 21	1	195	217	189	0.524
	2	193	226	181	0.567
	3	194	222	183	0.545
	4	202	233	184	0.473
	Average	196	225	184	0.527
Tone 25	1	251	219	298	0.510
	2	243	211	284	0.518
	3	257	213	304	0.439
	4	270	235	305	0.482
	Average	255	219	298	0.487
Tone 33	1	277	275	276	0.633
	2	272	267	270	0.516
	3	272	269	291	0.529
	4	276	281	247	0.452
	Average	274	273	271	0.532

Appendix C. Norwegian monolingual and bilingual infants' discrimination of Cantonese tones



Notes. Figures represent monolingual (left) and bilingual (right) infants' looking time towards two tone contrasts at 5 months (top) and 10 months (bottom). The x-axis represents tone contrast saliency. The y-axis represents looking time towards trial type, that is habituated (light bar) and new (dark bar) trials in the test block. Error bars = ±1 SE.

Data availability

Data will be made available on request.

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