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Perception of tones by infants learning a non-tone language

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ABSTRACT

This article examines the perception of tones by non-tone-language-learning (non-tone-learning) infants between 5 and 18 months in a study that reveals infants' initial sensitivity to tonal contrasts, deterioration yet plasticity of tonal sensitivity at the end of the first year, and a perceptual rebound in the second year. Dutch infants in five age groups were tested on their ability to discriminate a tonal contrast of Mandarin Chinese as well as a contracted tonal contrast. Infants are able to discriminate tonal contrasts at 5–6 months, and their tonal sensitivity deteriorates at around 9 months. However, the sensitivity rebound sat 17–18 months. Non-tone-learning infants' tonal perception is elastic, as is shown by the influence of acoustic salience and distributional learning: (1) a salient contrast may remain discriminable throughout infancy whereas a less salient one does not; (2) a bimodal distribution in tonal exposure increases non-tone-learning infants' discrimination ability during the trough in sensitivity to tonal contrasts at 11–12 months. These novel findings reveal non-tone-learning infants' U-shaped pattern in tone perception, and display their perceptual flexibility.

1. Introduction

Infants have an astounding sensitivity to the nuances of speech which begins even before birth, parts of which are enhanced, and parts of which are mostly lost by adulthood. During the last four decades, much attention has been paid to infant speech perception and how it is shaped by the ambient environment. We know that newborns distinguish different pitch contours at the word level (Nazzi, Floccia, & Bertoncini, 1998); they can discriminate between non-native languages from different rhythmic classes (Mehler et al., 1988; Nazzi, Bertoncini, & Mehler, 1998), and between words with different patterns of lexical stress (Sansavini, Bertoncini, & Giovanelli, 1997). During the first year after birth, they shift from attending to contrasts, regardless of whether they are native or non-native, to a heavier focus on contrasts within their native language(s). This process of tuning in to the native language inventories manifests itself in three distinct ways: maintenance of the initial sensitivity to native contrasts (Burns, Yoshida, Hill, & Werker, 2007), a tendency to start tuning out non-native contrasts (Anderson, Morgan, & White, 2003), and an increasing ability to discriminate the more subtle native contrasts (Kuhl et al., 2006; Polka, Colantonio, & Sundara, 2001; Sundara, Polka, & Genesee, 2006; Tsao, Liu, & Kuhl, 2006). We also know that the shift from universal to language-specific perception for consonants and vowels occurs around 8–12 months and 6–8 months respectively, after which infants' discrimination of non-native consonants and vowels greatly deteriorates (e.g., Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Kuhl et al., 2008; Pegg & Werker, 1997; Polka & Werker, 1994; Sebastián-Gallés, 2006; Werker, Gilbert, Humphrey, & Tees, 1981; Werker & Tees, 1984). What is less well-understood is

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the developmental trajectory of lexical tones. The present study investigates this aspect of infants' speech perception in an effort to expand current knowledge, especially concerning non-tone-learning infants' tonal sensitivity.

In tone languages (e.g., Mandarin Chinese), lexical tones are pitch variations used to distinguish meaning at the word level, a linguistic function lacking in non-tone languages (e.g., Dutch). It is largely unknown how non-tone-language learning infants' initial sensitivity to lexical tone is reshaped in the course of the first year of life, as a function of maturational factors and possibly of input factors, such as intonation. For this reason, tone is a promising area of investigation for the universal to language-specific perceptual change in the first year of life. Understanding non-tone-learning infants' tonal perceptual pattern helps reveal the nature of the perceptual tuning period in relation to the input distributions and properties (e.g., contrast salience).

Previous studies suggest different developmental patterns between tone-learning and non-tone-learning infants in the first year of life. On the one hand, tone-learning infants seem to retain continuous sensitivity to tonal contrasts. Mandarin and Cantonese infants showed language-specific preference as early as 4 months in Cantonese tone discrimination (Yeung, Chen, & Werker, 2013). Mandarin infants of both 6 and 9 months retained their sensitivity to Thai tonal contrasts (Mattock & Burnham, 2006). Yorùbá infants of 6 months were more attentive to Yorùbá tones than English infants (Harrison, 2000), revealing early native enhancement. On the other hand, non-tone-learning infants displayed perceptual deterioration in the second half of the first year of life. Reduced sensitivity to Thai tones was found in 9-month-old English infants compared to 4- and 6-month-olds, whereas sensitivity to musical tonal contrasts was retained across ages (Mattock & Burnham, 2006; Mattock, Molnar, Polka, & Burnham, 2008). Similarly, Yeung et al. (2013) found a decline in Cantonese tone discrimination with English infants from 4 to 9 months. Taken together, these studies suggest that language-specific perception of tonal contrasts occurs between 4 and 9 months.

Infants discriminate non-native consonant and vowel contrasts poorly after tuning in to the native sound inventory, and this lack of sensitivity extends to adulthood (Bosch & Sebastián-Gallés, 2005; Tsao, Liu, Kuhl, & Tseng, 2000; Tsushima et al., 1994). However, non-native adult listeners are sensitive to lexical tones, which they perceive acoustically (Francis, Ciocca, Ma, & Fenn, 2008; Gandour et al., 2000; Hallé, Chang, & Best, 2004; Kaan, Barkley, Bao, & Wayland, 2008; Xu, Gandour, & Francis, 2006). Recent studies reveal a similar pattern for Dutch adults, who display ceiling performance when discriminating a high-level (T1) vs. high-falling (T4) tonal contrast in Mandarin Chinese (Liu, Chen, & Kager, in preparation).

Considering non-tone-learning infants' deteriorating perceptual sensitivity to tonal contrasts in the first year and non-tone-learning adult listeners' success in tone discrimination, a rebound of tonal sensitivity must occur at some point after 9 months and prior to adulthood, whether abruptly or gradually. Nevertheless, to our knowledge, no study has directly investigated the timeline and nature of this rebound. The transitional time period arguably starts from a deterioration of universal sensitivity to tonal contrasts and ends with a rebound of acoustic sensitivity. The primary questions are: What is the developmental pattern of non-tone-learning infants' tone perception during infancy? What is the developmental time window of their rebound of tonal perception? To answer these questions, the discrimination ability of a wide age range of infants was examined.

Going back to language-specific perceptual tuning, it has been shown that acoustic salience plays a role. Some consonant and vowel studies focusing on the perceptual change in the first year propose that the acoustic salience of a contrast varies as a function of the distance in perceptual space between the two members of the contrast (Narayan, Werker, & Beddor, 2010; Sebastián-Gallés & Bosch, 2009), yet little is known about the relationship between acoustic salience and tone perceptual development. It remains unknown whether a unique trajectory exists for each tonal contrast that is related to the relative degree of contrast salience. Yeung et al. (2013) attribute the perception differences between native and non-native tone-learning infants to their attention to various acoustic cues, such as F0 level and direction. However, infant studies using tonal stimuli to directly manipulate these cues have not yet been conducted. The next research question of the current study is: How does the acoustic salience of a tonal contrast influence non-tone-learning infants' tone discrimination along the developmental trajectory? To answer this question, the pitch contour of a natural tonal contrast was manipulated in order to compare two contrasts with different degrees of salience along a single acoustic dimension.

Regarding flexibility in the non-native perception of tones, one final question remains. It is not known whether non-tone-language listeners' sensitivity to tonal contrasts goes through a stage where it is behaviorally absent after tuning in to the native sound inventory (a scenario which we judge to be unlikely), or whether sensitivity is continuous but weakened before reaching the rebound point. Werker and Tees (2005) proposed that perceptual reorganization, the process of change from universal to language-specific perception in the first year of life, should be viewed as an "optimal period" instead of a clear-cut "critical period" since "both the onset and offset of openness to experience is variable rather than absolute" (p.233). The offset of language-specific perceptual tuning of tonal contrasts has been argued to be around 9 months (Mattock & Burnham, 2006; Mattock et al., 2008; Yeung et al., 2013). However, the nature of non-tone-learning infants' tone perception after the offset remains unclear. Hence, our last research question is: How flexible is non-tone-learning infants' tone perception at the stage when their tonal sensitivity is at its minimum?

Statistical learning provides a way of addressing the perceptual flexibility of the period in which non-native listeners' sensitivity to tonal contrasts is at its worst. Statistical learning refers to infants' ability to acquire information about distributions of elements in the input (Saffran, Aslin, & Newport, 1996). Maye, Werker, and Gerken (2002) found that input frequency distributions influenced 6- and 8-month-old English infants' perception, in that exposure to a unimodal distribution hindered infants' perception of a native contrast. In a follow up study, Maye, Weiss, and Aslin (2008) found that exposure to a bimodal distribution endowed 8-month-olds with an enhanced ability to discriminate a difficult contrast. At 10 months, English infants also benefited from bimodal exposure to a difficult contrast, although they required more exposure than younger infants (Yoshida, Pons, Maye, & Werker, 2010). In sum, infants are able to use statistical learning to track the linguistic relevance of properties of speech sounds in the second half of the first year. In this study, we examined infants' plasticity of tone perception through statistical learning.

Taken together, the set of experiments on tone discrimination presented in this study aims to provide a comprehensive map of the development of non-tone-learning infants' perception of lexical tones during the first year of life, and well into the second year. To summarize, the research questions of the current study are: (1) What is the developmental pattern of tone perception in non-tone-learning infants throughout infancy? What is the developmental time window of their rebound of tonal perception? (2) How does the acoustic salience of a tonal contrast influence non-tone-learning infants' tone perception along the developmental trajectory? (3) How flexible is non-tone-learning infants' tone perception at the trough of tonal sensitivity? The first two questions will be addressed by Experiments 1 and 2, and the last question by Experiment 3.

2. Experiment 1

A cross-sectional discrimination task was carried out to explore Dutch infants' tonal perception patterns via a Mandarin high-level vs. high-falling tonal contrast.

2.1. Stimuli

Four lexical tones exist in Mandarin Chinese (Fig. 1): high-level (T1), middle-rising (T2), low-dipping (T3) and high-falling (T4). A Mandarin tonal contrast, high-level tone (T1) vs. high-falling tone (T4) was selected to create the stimuli. The tone-bearing syllable was /ta/. Both /ta1/ 'build' and /ta4/ 'big' are words in Mandarin. The productions of a Mandarin female speaker were recorded using the computer program Audacity[1] via a microphone (active speaker Genelec 1029A) in a sound-proof booth at Utrecht University's phonetics lab. For each sound, four natural T1–T4 pairs were recorded to create within-speaker variation. Fig. 2 represents the pitch contour of a T1–T4 pair of stimuli.

2.2. Participants

A total number of 163 normally developing 5–6, 8–9, 11–12, 14–15 and 17–18 month-old Dutch infants participated in Experiment 1. Data from 140 infants were incorporated into the analysis, giving a drop-out rate of 14%.

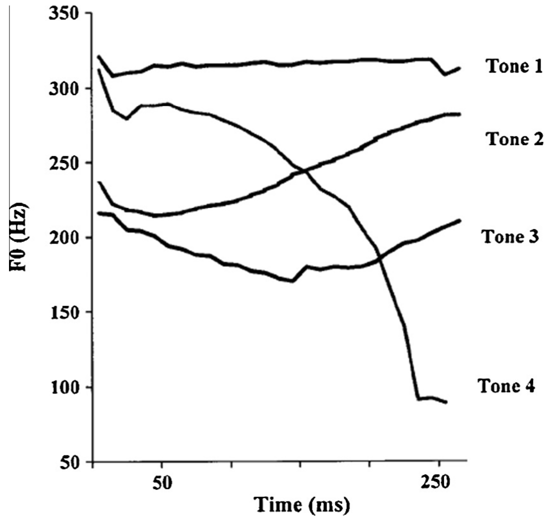

Fig. 1. Tones in Mandarin Chinese. *Source:* Wang, Jongman, and Sereno (2001).

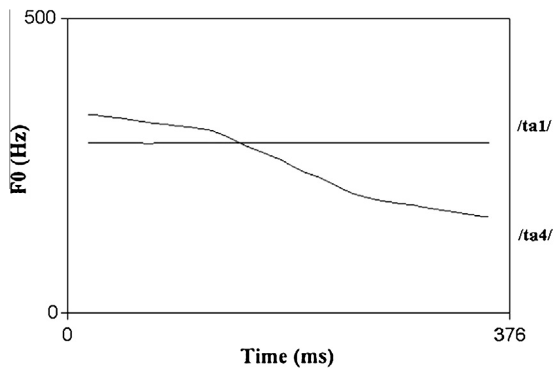

Fig. 2. T1–T4 contrast.

Data from 23 infants were excluded for the following reasons: fussing (8) or crying (3); failure to habituate after 25 trials in the habituation phase (4); experiment error (2); too short looking time (<2 s) in both trials in the change phase (2); and a looking time difference exceeding 2 standard deviations (SD) from the mean (4). In the final sample, each age group consisted of 28 infants.

2.3. Procedure

The infants went through a habituation, a test, and a post-test phase during the experiment. In the habituation phase, they heard repeated tokens of one tone. The habituation criterion was fulfilled when the mean looking time of the last three trials in the habituation phase fell below 65% of the mean looking time of the first three trials. The test phase then began with two trials of tokens of the other tone. The dependent variable was infant looking time during each trial, and the length of each trial was controlled by infant gazing; the first trial ended when the infant looked away for more than 2 s, and the next trial then began.

[1] Audacityopenresource: "http://audacity.sourceforge.net".

Discrimination was indicated by looking time rebound upon hearing the new stimulus. Within each age group, half of the infants were habituated on T1 and tested on T4, and the other half were habituated on T4 and tested on T1. The post-test phase included a novel stimulus verifying infants' general attention, followed by a children's song at the end.

During the experiment, infants sat on their caretakers' laps in the test booth, facing the screen and the camera. No visual or auditory distractions were present in the booth. An experimenter observed infants through a closed circuit TV in a room adjacent to the test booth, using a button box to record the infants' looking time. The test was run via a computer program (ZEP, Veenker, 2007). The inter-stimulus interval was set at 1 s in all phases. Any trial in which an infant's looking time was less than 2 s was excluded. The visual stimuli was a static target mark throughout the test phase for the first 4 age groups, and static female faces for infants of 17–18 month to better keep their attention.

2.4. Results

2.4.1. Habituation phase

Logs of mean looking time were used to form a normal distribution in order for the data to fit the requirements of ANOVA. The first three (Start window) and last three (End window) trials in the habituation phase were compared. The between-subjects factor was age, as outlined previously. A significant difference was observed for the main effect of (Start vs. End) window, $F\ (1, 135) = 1035.476$, $p < .001$. The interaction of age and window was not significant, $F\ (4, 135) = 2.084$, $p = .086$. Hence, we inferred that infants of all ages were habituated.

2.4.2. Test phase

The logs of the mean looking time were compared between the last two habituation trials and the two test trials using a repeated measures ANOVA. The between-subjects factor was age. The main effect of phase change (the difference between the two last trials in the habituation phase and the two trials in the test phase) was significant,[2] $F\ (1, 135) = 123.682$, $p < .001$. The interaction of age and phase change was not significant, $F\ (4, 135) = 1.612$, $p = .175$. Hence, infants in all age groups successfully discriminated the contrast. Although the interaction was not significant, the data suggest that the intrinsic strength of discrimination as indicated by the looking time difference is lowest during the second half of the first year of life.[3] Infants seem to present a U-shaped discrimination pattern.

2.5. Discussion

All age groups displayed successful discrimination of the Mandarin Chinese T1–T4 contrast. Experiment 1 thus provides evidence for a tonal contrast to which non-tone-learning infants' sensitivity is retained during and even after the language-specific perceptual tuning period as established by previous studies. Previous studies show that non-tone-learning infants uniformly lose tonal sensitivity at around 9 months. The current pattern of perceptual sensitivity being maintained across age was not observed in previous literature. Instead, this finding resembles the pattern of non-native perception of the German front-back high vowel /y/–/u/ contrast (Polka & Bohn, 1996).

Although tonal sensitivity was retained at all 5 ages, Fig. 3 suggests that the strength of discrimination is lowest in the second half of the first year of life. This suggests that the language-specific tuning found in previous studies may still have an impact on discrimination, yet the tonal contrast is salient enough to be discriminated by non-tone-learning infants across age. The overall finding seems to be in line with tonal perceptual reorganization, and it also raises the possibility that the salience of a tonal contrast may play a role in non-tone-learning infants' perception of tones.

With regard to the hypothesis that the tonal developmental patterns may vary for individual tonal contrasts stated in the introduction, the current results, in relation to previous findings (Mattock & Burnham, 2006; Yeung et al., 2013), suggest that infants' perceptual patterns are indeed contrast-dependent, with deterioration of perceptual sensitivity varying as a function of tonal contrast. Experiment 2 further investigates to what extent tonal developmental patterns are contrast-specific, by addressing the question how acoustic salience influences non-tone-learning infants' tone perception. We hypothesize that the U-shape pattern suggested by Experiment 1 will become evident in the next experiment with a tonal contrast of reduced salience.

3. Experiment 2

To investigate the effect of acoustic salience on non-tone-learning infants' tone perception along the developmental trajectory, the same discrimination task

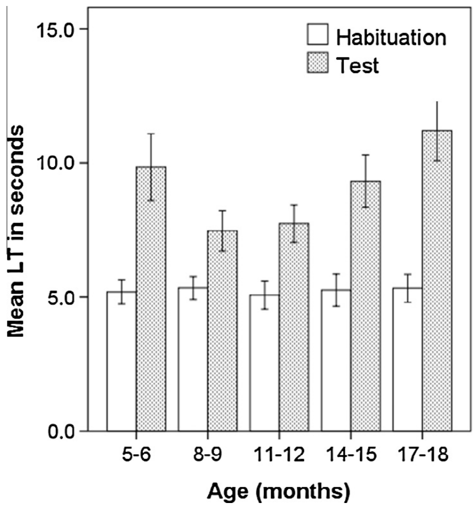

Fig. 3. Mean looking time of the two last trials in the habituation phase and the two trials in the test phase (Error bar: ±1 SE).

[2] As no re-presentation of habituation tones appeared in test trials, the results could be due to regression to the mean following attainment of the habituation criterion. However, this interpretation is unlikely given the different performances across age groups.

[3] We thank the anonymous reviewer of Cognition for pointing this out.

was carried out using an acoustically contracted contrast. Multiple acoustic cues, in particular duration, intensity, F0 level (pitch height), and F0 direction (pitch contour) contribute to the salience of a tonal contrast. To prevent any possible interference from speech cues other than pitch, only F0 was manipulated, leaving F0 direction as its sole cue. Presumably, the contracted contrast used here comes close to a natural contrast, as it resembles a contrast in the Jinan dialect (T2–T4, Hou, 1998).

3.1. Stimuli

The four natural Mandarin T1–T4 pairs as used in Experiment 1 were further manipulated via PRAAT (Boersma & Weenink, 2009). The pitch distance between T1 and T4 was contracted to two F0 values occurring at 3/8 and 3/4 of the pitch distance of the original contrast, respectively, by introducing four interpolation points along the pitch contours (at 0%, 33%, 67% and 100%, see Fig. 4). The new contrast shares precisely the same acoustic properties with the T1–T4 contrast used in Experiment 1 except for featuring a narrower distance between the pitch contours, thus shrinking the perceptual distance between the two tokens. In other words, the acoustic salience of this phonetic contrast is weakened by a pure manipulation of F0. Four pairs of the contracted contrast were generated to account for within speaker variation.

3.2. Participants

A total number of 171 normally developing Dutch infants participated in the study of the same 5 ages as in Experiment 1: from 5–6 months to 17–18 months. Data from 140 infants were eventually incorporated into the analysis, giving a drop-out rate of 18%, slightly higher than Experiment 1. The data for the 31 infants were excluded for: fussing (5) or crying (1); failure to habituate after 25 trials in the habituation phase (3); too short looking time (<2 s) on both change trials (12); and looking time differences exceeding 2 SD from the mean (10). In the final sample, each age group consisted of 28 infants.

3.3. Procedure

Infants were tested under precisely the same conditions, including instruction, location, equipment and procedure as in Experiment 1.

3.4. Results

3.4.1. Habituation phase

An analysis identical to that in Experiment 1 was conducted. In the habituation phase, the main effect of window was significant, F (1, 135) = 649.286, $p < .001$. The interaction of age and window was not significant, F (4, 135) = 0.497, $p = .738$. Hence, infants of all ages were habituated.

3.4.2. Test phase

The main effect of phase change was significant, F (1, 135) = 8.650, $p = .004$. The interaction of age and phase

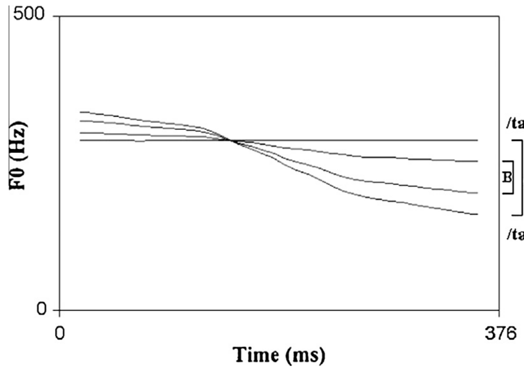

Fig. 4. T1–T4 [A] and contracted T1–T4 [B] contrasts.

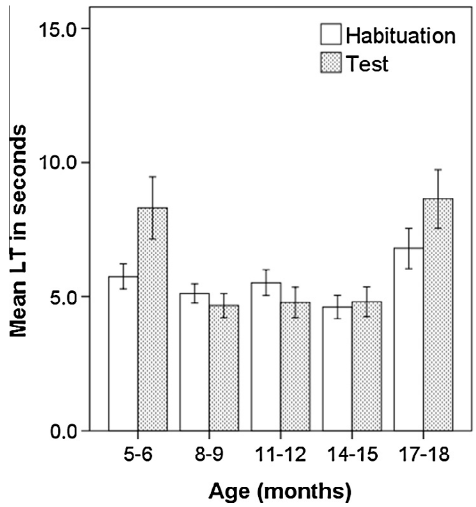

Fig. 5. Mean looking time of the two last trials in the habituation phase and the two trials in the test phase (Error bar: ±1 SE).

change was significant, F (4, 135) = 2.686, $p = .034$. Pairwise comparisons revealed that the first and the last age groups behaved significantly differently from the three age groups in the middle (Fig. 5). Pairwise comparisons showed that the difference between test and habituation was significantly bigger in the 5–6 and 17–18-month-olds than in the 8–9, 11–12 and 14–15-month-olds (largest $p < .018$). Looking into the individual age groups, only infants of 5–6 months ($p = .004$) and 17-18 month ($p = .018$) but not the other three age groups (smallest $p > .117$) discriminated the contrast in the phase change.

3.5. Discussion

Unlike Experiment 1, only infants of 5–6 and 17–18 months, but not the intermediate age groups, discriminated the contrast. The early decline in sensitivity provides evidence for tonal perceptual reorganization. Dutch infants show an early tonal sensitivity at around 5–6 months, and their sensitivity greatly deteriorates at approximately 8–9 months, compatible with Mattock and Burnham (2006).

This developmental pattern accords with previous studies using different tonal contrasts and testing non-tone-learning infants from different language backgrounds.

Importantly, a previously unknown finding is that, by the age of 17–18 months, a rebound of tonal sensitivity has occurred for non-tone-learning infants. Such a U-shaped developmental pattern is not unexpected given previous findings documenting non-native adult acoustic sensitivity (Hallé et al., 2004; Liu et al., in preparation). However, we provide the first evidence to show that the time window of this perceptual rebound occurs as early as in the first two years. The important issue of what may explain the rebound of perceptual sensitivity will be taken up in the general discussion.

Comparing the results of Experiments 1 and 2 helps us understand not only non-tone-learning infants' tonal developmental pattern but also how acoustic salience influences these infants' tone perception. Both contrasts undergo perceptual changes in the first year of life, and the strength of discrimination seems to be influenced by the salience of the contrast. Findings of the two experiments suggest that the time window during which tonal sensitivity declines and rebounds seems relatively constant, and it shows little if any fluctuation as a function of the salience of the contrast: a decline occurs at 8–9 months; a trough in the second half of the first year; and an increase near the end of the second year of life.

With respect to the U-shaped developmental pattern discovered in Experiment 2, the question now arises to what degree non-tone-learning infants have reduced their sensitivity to tonal contrasts at 11–12 months before they begin to exhibit rebound, or preserve residual flexibility in tonal sensitivity. This question will be addressed in the next experiment.

4. Experiment 3

Experiment 3 addresses the residual flexibility of non-tone-learning infants' tone perception during perceptual organization. It investigates how statistical learning influences non-tone-learning infants' discrimination of a tonal contrast after the perceptual decline by 9 months, yet before the rebound of tonal sensitivity. Based on the results of Experiment 2, the age at which discrimination was at its minimum was set at 11–12 months.

4.1. Stimuli

The distances (in Hz) between temporally aligned points of 4pairs of tokens of the same contrast used in Experiment 1 were divided into seven equal steps each, at four points in time (0%, 33%, 67% and 100%). Then each of the in-between points was connected by simple interpolation to produce new pitch contours. In this way, eight stimuli including the endpoint contours were created for one continuum from stimulus 1 (/ta1/) to stimulus 8 (/ta4/) (Fig. 6), and 32 stimuli were generated in total for the four continua as multiple tokens.

4.2. Participants

43 normally developing 11–12-month-old Dutch infants participated in the study. Data of 32 infants were eventually included in the analysis; that is, there was a drop-out rate of 26%. The data for 11 infants were excluded for: fussing (6); failure to habituate after 25 trials in the habituation phase (1); too short looking time (<2 s) on both change trials (2); looking time differed by more than 2 SD from the mean in the phase change (1); parental interference (1). In the final sample, each unimodal or bimodal group consisted of 16 infants.

4.3. Procedure

Infants followed the statistical learning paradigm of Maye et al. (2008). The paradigm consisted of three phases: familiarization, habituation and test. In contrast to Experiments 1 and 2, Experiment 3 included an additional familiarization phase. Infants were randomly assigned to two groups. During the familiarization phase, the two groups were each trained on a different type of distribution condition: unimodal or bimodal. The two modal distributions differ in the frequency of exposure to tonal stimuli along the 8-step continuum, in that a bimodal distribution creates a contrastive distribution, whereas a unimodal distribution does not (Fig. 7). In both conditions, a total number of 128 trials occurred, with a total duration of 3 min. The hypothesis was that a bimodal distribution would convey the linguistic importance of a phonetic contrast, thus facilitating' the discrimination of speech sounds within the continuum, whereas a unimodal distribution would result in inattention to the phonetic contrast. After the familiarization phase, infants were exposed to tokens of stimuli 6 in the habituation phase. When habituated to the stimulus, infants progressed to the test phase and heard two trials of tokens representing stimuli 3. Note that stimuli 3 and 6 were exactly the same stimuli tested in Experiment 2. Infants' looking time was recorded for each trial.

4.4. Results

4.4.1. Habituation phase

Logs of mean looking time were used to form a normal distribution in order for the data to fit a repeated measures

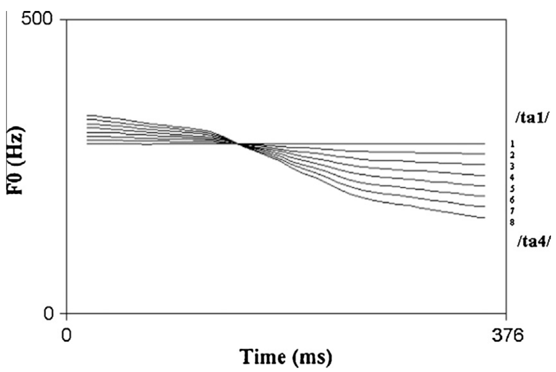

Fig. 6. 8-Steps along a T1–T4 continuum.

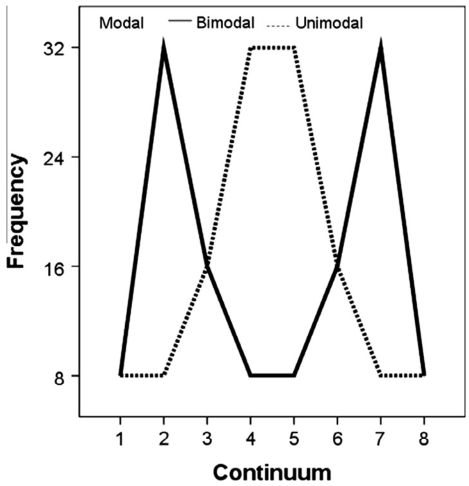

Fig. 7. Unimodal and bimodal frequency distributions. Horizontal: 8-step of stimuli along the T1–T4 continuum. Vertical: token frequency in the familiarization phase.

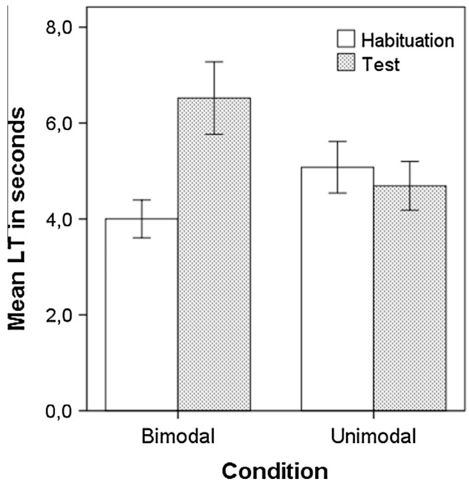

Fig. 8. Mean looking time of the two last trials in the habituation phase and the two trials in the test phase (Error bar: ±1 SE).

ANOVA. The first three (Start window) and last three (End window) trials in the habituation phase were compared. The between-subjects factor was the two-level familiarization condition (Unimodal vs. Bimodal). There was a main effect of window in the habituation phase, $F(1, 30) = 163.393$, $p < .001$. The interaction of condition and looking time window was not significant, $F(1, 30) = 0.331$, $p = .569$. Hence, infants under both conditions were habituated.

4.4.2. Test phase

Logs of mean looking time were compared between the two test trials and the last two habituation trials using a repeated measures ANOVA. The between-subjects factor was the two-level familiarization condition. The main effect of phase change was not significant, $F(1, 30) = 3.358$, $p = .077$; but the interaction of familiarization condition and phase change was significant, $F(1, 30) = 7.019$, $p = .013$. Looking into the individual familiarization conditions, only infants of bimodal ($p = .016$) but not unimodal ($p = .475$) discriminated the contrast in the phase change. At this age, infants in the bimodal condition, but not the unimodal condition, discriminated the contrast. The raw looking times are graphically presented in Fig. 8 for ease of understanding.

4.5. Discussion

Dutch infants discriminated the contrast under bimodal conditions at 11–12 months, an age that matches the trough of the U-shaped sensitivity pattern. Those in the unimodal condition failed to discriminate the contrast, behaving like their peers without the aid of statistical learning. Hence, exposure to a bimodal distribution can promote non-tone-learning infants' perception of an acoustically less salient contrast, even at the trough of sensitivity. This novel finding implies that tone perception may remain flexible throughout infancy. This result has a counterpart in earlier studies on non-native segmental perception: 10–11-month-old infants retain a residual sensitivity to non-native consonantal contrasts (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). It is also consistent with earlier statistical learning studies on non-native consonant perception (Yoshida et al., 2010). The current findings extend the evidence for flexibility of non-native discrimination to the non-segmental (prosodic) level. Another implication resides in the interpretation of how sound distributions may impact infants' perception. Maye et al. (2002, 2008) suggest that sound distributions in the input received by infants drive the language-specific perceptual tuning process. This includes two scenarios, the deterioration of sensitivity to non-native contrasts and the increase of sensitivity to difficult native contrasts. Since 11–12-month-old infants are not sensitive to the same tonal contrast in a pure discrimination task in Experiment 2, the fact that non-tone-learning infants can successfully discriminate the less salient contrast in Experiment 3 should be attributed to the enhancement effect of the bimodal exposure. We speculate a further interpretation: for infants whose ambient input does not contain a particular contrast, exposure to a bimodal distribution enhances discrimination (which applies to the current case), whereas for infants whose ambient input contains a particular contrast, exposure to a unimodal distribution reduces discrimination of this contrast (the mirror-image case).

In sum, Experiment 3 shows that 11–12-month-old Dutch infants are still flexible enough to a low-salience tonal contrast given the "right" type of frequency exposure. This is evidence for non-tone-learning infants' perceptual flexibility at the lowest point of sensitivity, reflecting a continuous sensitivity to tonal contrasts.

5. General discussion

The current study explores the developmental pattern of non-tone-learning infants' tone perception and displays several new findings: non-tone-learning infants' tonal sensitivity rebounds at a later stage, is salience-dependent, and can be enhanced by a bimodal distributional input at its trough.

Neonates are sensitive to prosodic information, and their perception already shows the signature of native speech input, indicating prenatal prosodic experience (Byers-Heinlein, Burns, & Werker, 2010). Although infants showed a language-specific perceptual pattern of tonal contrasts as early as 4 months (Yeung et al., 2013), their perception is still greatly influenced by the initial sensitivity to prosodic information at 5–6 months. This indicates that both tonal experience and acoustic salience play a role in infants' tone perception.

The sensitivity to tonal contrasts decreases at around 8–9 months in non-tone-learning infants. This finding seems ubiquitous across studies (Mattock & Burnham, 2006; Mattock et al., 2008; Yeung et al., 2013). The perceptual change is likely to be the result of a lack of relevant input, namely a systematic exposure to word-level pitch contrasts, in a non-tone-language environment.

At 11–12 months, non-tone-learning infants exposed to a bimodal distribution during familiarization show an increase in their discrimination of tones, indicating the retention of residual sensitivity to tonal contrasts. Similar results suggesting perceptual plasticity have been found with younger infants (Kuhl, Tsao, & Liu, 2003). This is compatible with the finding that a bimodal exposure may positively alter infants' perception (Yoshida et al., 2010).

Having tested a broad age range of non-tone-learning individuals, a rebound of tonal sensitivity is found in the second year of life, forming a U-shaped overall developmental pattern for non-tone-learning infants. This rebound of sensitivity is not unexpected, given non-tone-language adult listeners' sensitivity to tonal contrasts (Gandour et al., 2000; Hallé et al., 2004; Kaan et al., 2008; Xu et al., 2006). We hypothesize that this sensitivity rebound in infancy might be related to the ongoing acquisition of knowledge of native intonation. Specifically, non-tone-learning infants may benefit from the accumulated exposure to the native intonation system, assuming that they have already started analysing pitch variation in relation to pragmatic meaning by the end of their first year. Similar to lexical tones, intonation is realized to a large extent by means of pitch variation, yet at an utterance level instead of a word level. Previous studies have shown that infants are sensitive to certain prosodic cues at the utterance level in the first year of life (Männel & Friederici, 2009; Nazzi, Nelson, Jusczyk, & Jusczyk, 2000; Pannekamp, Weber, & Friederici, 2006; Seidl & Cristià, 2008). In a word recognition task, Dutch 14-month-olds tended to recognize target words better when the intonation contour was pragmatically appropriate than when pragmatically inappropriate (Chen & Fikkert, 2007; Fikkert & Chen, 2011). At 21 months, various aspects of European Portuguese infants' intonation production (e.g., F0 alignment) have become adult-like (Frota & Vigário, 2008). Similarly, 24-month-old Catalan children could finely control F0 alignment but not F0 scaling of syllables in a task eliciting statement intonation patterns (Vanrell, Prieto, Astruc, Payne, & Post, 2010). It appears that knowledge of the native intonation system is already being acquired in the first year of life, but is not stabilized even after the second year due to its complex linguistic use. Acquisition of intonation is likely to be a cumulative process, requiring integration of knowledge about pitch contours, grammatical structure, and pragmatic meaning. For this reason, benefits of early exposure to intonation may emerge only at a relatively late stage rather than in early infancy. Dutch, as other languages, has an intonation system involving meaningful variation in pitch contours (Gussenhoven, 2005). Similarities can be observed between the tones in our study and Dutch intonation. Mandarin high-falling T4, used in the current study, is both acoustically and perceptually quite similar to the falling H * L nuclear pitch accent in Dutch. Dutch infants' sensitivity to falling pitch contours may extend to non-tone-learning infants with different language backgrounds, since falling contours predominate in infants' productions from 3 to 12 months (Kent & Bauer, 1985; Kent & Murray, 1982). It is plausible that the Dutch infants in our experiments use their accumulated knowledge of pitch variation in intonation to facilitate their tone perception, as was shown at 17–18 months in Experiment 2. This hypothesis predicts that non-tone-learning infants from different intonation backgrounds may present different perceptual patterns to a certain tonal contrast especially at an older age.

The manipulation of salience in Experiments 1 and 2 reveals its relevance for the extent to which infants retain a residual sensitivity to non-native tonal contrasts after the perceptual decline, similarly to previous studies of consonants (Narayan et al., 2010). Throughout their development, Dutch infants have little or no difficulty discriminating a salient tonal contrast of Mandarin, yet they do not succeed on a more subtle contrast in which the difference between pitch contours has been made less extreme. Perception is affected more strongly for a phonetically less salient non-native contrast than for a salient one during the language-specific perceptual tuning period. In other words, psychoacoustic salience may determine the "robustness" of a contrast (Burnham, 1986). This contrast strength interpretation is in line with the claim of Stevens and Keyser (1989) that there is a similar relation between phonological features and perceptual saliency, although, unlike consonants, the effect of F0 direction tested in the current study is not likely to be a binary distinction. Rather, contrast strength ("robustness") and perceptual salience may depend on the distance between the pitch contours.

To summarize, the developmental pattern of non-tone-learning infants' tone perception is U-shaped, with an initial sensitivity to tonal contrasts, sensitivity deteriorating at 8–9 months, and rebounding at around 17–18 months. The rebound may be influenced by the accumulated knowledge of the native intonation system. Tonal perception is continuous and plastic across development. Evidence for perceptual continuity comes from three sources: a salient tonal contrast can be discriminated throughout infancy (Experiment 1); the tonal sensitivity rebounds in the second year (Experiment 2); and exposure to a bimodal distribution enhances tonal discrimination at the stage at which tone perception is at its poorest (Experiment 3). These findings provide a comprehensive developmental trajectory of non-tone-learning infants' tone perception in the first two years of life.

Several key issues are crucial for future research. First, it remains unclear how non-tone-learning infants perceive tones at different ages. We do hypothesize that non-tone-learning infants' perception has become adult-like at the rebound stage, but leave the nature of perception before that period open to discussion. It could be that tonal perception is linguistic for all infants initially, and then shifts to acoustic for non-tone-learning infants. Alternatively, tonal perception may be acoustic for all infants in the beginning and tone-learning infants' perception of tones becomes linguistic, whereas the perception of non-tone-learning infants remains acoustic given their respective language environment. These possibilities are closely related to the nature of the tonal perceptual decline in the first year of life. Infant brain-imaging studies exploring in which brain area the tones are processed may shed light on this question, given that the left hemisphere would be more involved in linguistic perception. In addition, word learning experiments involving the association between tones and meanings may also reveal the nature of tone perception in non-tone-learning infants. Previous studies showed that English children of 29 months did not treat the pitch change as relevant when learning words (Quam & Swingley, 2010). Younger infants need to be tested in future studies.

Second, the current study investigated two tonal contrasts of different degrees of salience across ages, revealing two different perceptual patterns. However, the data seemed to present certain gradualness in the susceptibility to perceptual decline to non-native contrasts depending on contrast salience. It remains unclear how acoustic salience affects the perceptual pattern of a particular tonal contrast. More contrasts need to be tested to understand whether each tonal contrast follows its own developmental pattern.

Third, we suggest that additional non-native contrasts, tonal and segmental, as well as infants of a wider age range, should be tested in any further studies regarding the issue of perceptual reorganization. Testing infants of a wide age range may be crucial since studies on infants' speech perception typically test two age groups within a short age range, and may potentially miss the complete picture. An important question is whether the perceptual decline-plus-rebound pattern, as documented here, can be replicated for non-native segmental contrasts.

Fourth, in order to study the potential influence of intonation on lexical tone perception, cross-linguistic studies may compare the perceptual patterns for lexical tone and intonation of infants from languages with relatively rich intonation systems (e.g., English, Dutch) and languages with relatively poor intonation systems (e.g., French, Korean). The potential facilitative effect of intonation contours on infants' perception of acoustically similar tonal categories should also be studied for pitch-accent languages (e.g., Tokyo Japanese).

Fifth, and finally, although the contracted tonal contrast used in Experiment 2 is not a natural contrast of Mandarin, we predict the effect of acoustic salience on perception to hold for natural contrasts as well. Future research can test natural tones in tone languages while drawing material from richer tone systems in which multiple natural contrasts can be formed (e.g., Cantonese, Vietnamese). Also, the developmental pattern of Mandarin Chinese infants needs to be studied with the same stimuli as used in the current study.

In summary, putting all the future research together will provide us with a detailed map of infants' learning and perception of lexical tones, and subsequently the language acquisition process from a suprasegmental angle in the beginning of life.

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