



<b>Title</b>	<b>The discrimination of the fundamental frequency of complex tones by normally hearing children</b>
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The Discrimination of the Fundamental Frequency  
of Complex Tones by Normally Hearing Children

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### Abstract

This study investigated the fundamental frequency (*F0*) discrimination of complex tones by children. Children aged 3, 4, 5, 6, 10 and young adults participated in the test. They were asked to indicate whether two pairs of tones were the same or different. The *F0* discrimination ability of participants was examined with reference to standard tones of 120 and 250 Hz *F0*. The results showed children's *F0* discrimination ability under the 2 *F0*s reached adult level at about 4 years of age. No significant difference was found for the *F0* discrimination thresholds of participants at 120 and 250 Hz *F0* conditions. The findings have implications for further investigations on the development of *F0* discrimination in children and their linguistic abilities.

Pure tones seldom appear in nature (Martin & Clark, 2000). Nearly all communication sounds produced by humans are complex sounds (Medvedev, Chiao, & Kanwal, 2002). The perception of complex sounds is an important function of the human auditory system. The processing of auditory input, such as speech, requires the listener's ability to discriminate changes, in terms of different acoustic parameters such as frequency, intensity, and duration. Differences between questions and statements, the structures of utterances in terms of phrases, and emotional status and gender of speakers are all conveyed by different pitch patterns (Moore, 1995). The perception of pitch, relying on the ability to discriminate fundamental frequency ( $F_0$ ) changes in complex communication sounds is, thus, one of the critical elements for understanding speech of all languages.

In tonal languages, lexical tones differ primarily in terms of their pitch patterns (Bauer & Benedict, 1997). Thus,  $F_0$  discrimination ability plays an important role in discriminating different tones in tonal languages. The ability of Cantonese preschool children to perceive tones is one of the fundamental requirements in language development. Given this importance, it is useful to know the preschool children's ability of  $F_0$  discrimination.

Frequency difference limen (frequency DL) (also called just-noticeable difference in frequency) is the size of the smallest detectable change in pure tone frequency (Moore, 1997). The value of frequency DL varies when the base frequencies being compared are different. It was found that the threshold of frequency difference increased with increasing base

frequency above 1000 Hz (Weir, Jesteadt, & Green, 1977). Within an intermediate range of frequencies at around 1000 Hz, the frequency difference ( $\Delta f$ )/frequency ( $f$ ) is nearly constant at about  $\Delta f/f = 0.002$  (Yost, 2000). In other words, frequency DL can be as small as 1 Hz.

Recent studies show a gradually decreasing frequency DL in preschool children with increasing age, possibly due to the maturation effect of auditory systems in children (Jensen & Neff, 1993). Thompson, Cranford, and Hoyer (1999) showed that children's ability to discriminate pure tone frequency changes did not reach adult level until after 7 years old. They suggested maturation of peripheral and central auditory systems were required for children to achieve an auditory discrimination task. In adult control, the mean frequency discrimination threshold was found to be about 10 Hz (Bishop & McArthur, 2004).

The mentioned studies used pure tones as stimuli. However, as stated above, complex sounds occur more frequently in nature. They are the major communication sounds produced by human, which means they are the major auditory inputs in our daily life. Judgments on pitch differences in complex sounds will, therefore, provide relatively more relevant information for understanding speech perception. Flanagan and Saslow (1958) showed that frequency DL of complex tones (DLCs), by using synthetic vowels with constant fundamental frequency of 120 Hz, were about 0.3-0.5 Hz in adult. Klatt (1973) replicated the same measurement of DLCs in synthetic vowels and found very similar results as in the study by Flanagan and Saslow (1958).

Many studies on frequency discrimination recruited school-age children or adults as subjects. One possible explanation to recruit such subjects was because their performance tended to be less affected by any factors other than their frequency discriminating ability, such as cognitive and language abilities and maturation of auditory systems. Thompson et al. (1999) suggested that the sensory and/or cognitive skills necessary for frequency discrimination might not reach maturity until 7 years old. A relatively few studies were conducted on preschool children. One goal of the present study is to investigate the trend of the changes of *F0* DLCs beginning from preschool to school-aged children.

Grimault, Micheyl, Carlyon, Bacon, and Collet (2003) hypothesized that since encoding *F0* of complex tones might depend on encoding of the frequencies of the individual harmonics, training on pure tone frequency discrimination should improve *F0* discrimination. They found that training in pure tone frequency discrimination resulted in significant better *F0* discrimination. Base on their logic, since a decreasing frequency DLs on pure tone discrimination was found with increasing ages in several studies (e.g. Jensen & Neff, 1993), it is likely that the same trend would be found for complex tone *F0* discrimination in children when measuring the *F0* DLCs. This is the first hypothesis in the current study.

Moore (1995) suggested that for *F0* in the range of 100-400 Hz, very small changes, about 0.2%, in repetition rate of complex tones could be detected. According to G. A. Moore and B. C. J. Moore (2003a), when all the components in a harmonic complex had a fixed

amount of frequency-shift, the perceived pitch would roughly shift in the same direction proportionally. As a result, a same amount of change, larger than 0.2%, at lower  $F0$  (e.g. 120 Hz) should yield a larger perceived pitch difference than at higher  $F0$  (e.g. 250 Hz). For example, if complex tones of 120 and 250 Hz  $F0$  were shifted by 20 Hz, the perceived pitch would change for 16.7% (20/120) and 8.0% (20/250) respectively. With the same amount of  $F0$  change, the pitch change would be easier to detect at a lower  $F0$ . Therefore, a lower threshold at lower  $F0$  was expected. To investigate whether the above deduction was true for both preschool and school-aged children, the second aim of the study is to investigate if there is any difference on  $F0$  DLCs on higher and lower  $F0$  complex tones.

## Method

### *Participants*

Initially, a total 66 children participated in the experiment. There were 21 age-3 children (mean ages 3;06), 15 age-4 children (mean ages 4;08) and 10 children in each of the 5-year-old (mean ages 5;05), 6-year-old (mean ages 6;06) and 10-year-old (mean ages 10;08) group. They were all recruited from local kindergarten and primary school. Sixteen children (11 age-3 and 5 age-4) were excluded from the test at the end as they either failed to pass the practice session or failed to give reliable or valid responses in the test. In addition, 10 young adults aged from 18 to 25 (mean ages 22;08) were tested to serve as a control group. The adult subjects were recruited from the author's social circle based on their own willingness to

participate. The final participant sample in the study consisted of 10 subjects in each age group (3, 4, 5, 6, 10 and adult). Written consent (see Appendixes A and B) was obtained from adult subjects and from caregivers of children subjects before they participated in the experiment.

### *Pre-test Hearing Screening*

Hearing screening was carried out during the day of the test to ensure all participants had normal hearing. The hearing screening procedures included tympanometry, using a GSI 37 Auto Tympanometer, and pure-tone audiometry, using a Maden Electronics Micromate 304 Screening Audiometer. The criteria to pass the hearing screening was to get type A tympanogram and to be able to respond to pure tones of 500 Hz, 1000 Hz and 2000 Hz presented at 30 dB HL bilaterally.

### *Instrumentation*

All stimuli were presented to participants from a Toshiba laptop computer (model: VX/2W15LDSW) with Sigma Tel C-Major Audio sound card through a Sennheiser (model: HD280 professional) headphone. A Quest Electronics permissible sound level pressure meter (model: 125) was used to measure the auditory output from the headphone on the day of the test. The loudness of the stimuli was controlled and fixed to 85 dB SPL. Background noise was measured on the day of the test by using the same sound level pressure meter, and was below 50 dBA on each day of the test.



### *Stimuli*

Complex tones were synthesized by using Praat 4.3 computer program. All complex tones contained 10 harmonics, starting from the second to the eleventh, and were filtered using a formant filter centered at 700 Hz and with a 200 Hz bandwidth. Afterwards, the amplitude of tones was normalized. All the tones had a duration of 100 msec with 10 msec rise/fall time. Standard and comparison tones were made for the practice and test. The two tones were always presented in pair with interstimulus-interval (ISI) of 250 msec in each trial. The standard tone used in the practice was a complex tone with 150 Hz  $F_0$ . Comparison tone used in the practice had a fixed  $F_0$  of 195 Hz, that is, a 45 Hz shift relative to the standard tone. Standard tones used in the experimental session were the complex tones with either 120 or 250 Hz  $F_0$ . Comparison tones used in the experiment had higher  $F_0$  than the standard tones. The size of the  $F_0$  shift was 76.8, 38.4, 19.2, 9.6, 4.8, 2.4, 1.2, 0.6, 0.3, 0.15 or 0.075 Hz, relative to the base frequencies of 120 or 250 Hz.

Two pairs of stimuli were presented in each trial. The first tone pair was a sequence of the standard tone and a comparison tone in random order. The second pair consisted of the same standard and comparison tones with either the same or with reversed order as the first pair. There was an equal likelihood for both orders to appear. The two pairs were separated by 500 msec ISI in each trial.

### *Procedures*

Thompson et al. (1999) pointed out that preschool children did not have developed comparative and spatial language relation. The children might be unable to reliably use the verbal labeling (e.g. high / low) to refer to the nature of the perceived auditory stimuli (e.g. higher or lower pitch). According to Bishop and McArthur (2004), a task requiring relative judgments on stimuli (e.g. were the tones different?) minimizes the load on memory for temporal order, when compared with a task requiring both relative and absolute judgments on stimuli (e.g. was the first or second tone higher?). Since half of the participants in the current experiment were preschool children, a two-interval, two-alternative, forced choice (2I-2A-FC) task was implemented in order to reduce their memory demand on temporal order and to minimize difficulty of the task due to the requirement on comparative and spatial concepts.

Participants took part in a practice session prior to the experimental session. They took part in the later test session only if they passed the practice session.

Each participant was seated in a quiet room in front of a colour computer monitor individually. The experimenter sat next to the participant. Participants were instructed on the task and were told to give responses verbally to the experimenter. In both the practice and the experimental session, the participants heard two pairs of tones. They were then asked to indicate whether two pairs of tones were the same or different. After they gave a verbal response about 'same/difference', the experimenter clicked on the computer to record their

responses. After recording the responses and clicking 'next' button on the computer, the next trial began. If the  $F0$  difference between the standard tone and the comparison tone, within each interval, was too small for the participants to detect, they could not tell if there was a difference between the two tones. Hence, they could not make a correct judgment on telling if the pairs were the same or different. Therefore, the ability to judge if two intervals being the same or different indirectly indicated the  $F0$  discrimination ability of the participants.

From trial to trial, the  $F0$  difference between the standard tone and the comparison tone was varied adaptively in the experimental session, but was fixed in the practice. It was because the aim of the practice was to allow the participants to get familiarized with the procedure while the aim of the experimental session was to found out the thresholds of the  $F0$  discrimination of the participants. The details of the frequency change in each trial in both practice and test session was discussed later in the article.

According to B. C. J. Moore and G. A. Moore (2003b), a change of  $F0$  of 20% larger from the center  $F0$  was likely to be sufficiently large enough to be easily discriminated. In the practice, the size of  $F0$  shift was fixed to 45 Hz relative to a 150 Hz  $F0$  standard tone, which was large enough for the participants to understand the task.

To attract the young participants and to keep their attention on the test, visual images were presented simultaneously on the computer screen with the tones. A 'clean puppy heading upward' was presented when the interval contained a pair of lower-to-higher tones.

A 'dirty puppy heading downward' was presented when the interval contained a pair of higher-to-lower tones (see Appendixes C and D for images). The association of the 'puppies' with the direction of the pair of tones (i.e. high-to-low or low-to-high) facilitated them to understand what auditory information they needed to attend to and make their comparison of same/different on. In other words, the association helped them to understand that they should compare the pitch of the tones, but not other auditory parameters, such as loudness or the gap between the tones.

In the practice, visual image of a puppy was presented when the participants heard the first interval. The same puppy was presented if the second interval was of the same order as the first one. A different puppy was presented if the second pair was of the different order as the first interval. This was to facilitate the, especially preschool, participants to understand the requirement of the task and facilitate them to grasp the concept of comparing the tones in the two intervals. When they heard the same tones in the two intervals, they saw the same images associated with the presentation of the same first and second intervals, and then they learnt to give a response of 'same' and learnt to give a response of 'different' on vice versa situation.

Whenever the participants responded after a trial, they received immediate visual feedback of whether their response was correct. The same image of a 'puppy' as that presented simultaneously with the first interval would appear on the screen if a correct

response was made. Otherwise, an image of a 'red cross' (see Appendixes C and D for image) would appear. If the participants responded wrongly, the experimenter would explain verbally what happened before the next trial began. Figure 1 (see Appendix C) summarized the sequence of the auditory and visual presentation to the participants within a trial during the practice.

The practice session ended when the participant produced seven consecutive correct responses. This criterion ensured that the children understood the task. If the participants could not produce seven consecutive correct responses after a total 20 trials, they were excluded from the following experimental session.

The experimental session consisted of two blocks differing from the standard tone with *F0* of either 120 or 250 Hz. To balance practice effect, the order of presentations of the block of 120 and 250 Hz *F0* was counterbalanced across participants. Half number of participants in each age group did the 120 Hz *F0* block first and the 250 Hz *F0* block afterwards, while another half did in reverse order.

A similar procedure as in the practice was implemented in the experimental session. The difference was about the presentation of visual images and the *F0* difference between the standard and comparison tone. Figure 2 (see Appendix D) summarized the sequence of the auditory and visual presentation to the participants. Instead of presenting two identical/different 'puppies', a 'puppy' either heading upward or downward, depending on

the direction of tones, was presented on the computer screen simultaneously with the presentation of the first interval. A visual image of a 'house' (see Appendix D for image) was presented simultaneously with the presentation of the second interval.

The participants were told to pay attention to the tones and to do the same task as in the practice. They were told that a 'puppy' followed by a 'house' would be seen, instead two 'puppies' as in the practice. If they made a correct response, they could 'let the puppy out of the house'. Otherwise, the 'puppy' would be kept inside the 'house'. Same visual feedbacks as those in practice session were given after each trial. The experimenter would praise the participants for their correct responses made in every three trials and encourage them to try again in the next trial if they received a 'red cross' after an incorrect judgment.

A two-down one-up adaptive procedure (Levitt, 1971) was used to measure 70.7% correct identification on the psychometric function in the experimental session. The  $F0$  difference between the standard and comparison tones in the first and second intervals increased by a double following by an incorrect response (-) or a correct response followed by an incorrect response (+ -). The  $F0$  difference decreased by a half when two consecutive correct responses (+ +) were produced. The initial step size of both blocks of 120 and 250 Hz  $F0$  was 38.4 Hz. In the current study, a run was terminated after eight reversals.

A break of a few minutes was given to the participants when they finished the first block of the experimental session. A tangible reinforcement (a sticker or a stamp) was also

given to the children participants to appreciate their efforts on the task at the end of each block. The total testing time for each participant, including practice session, was about 25 minutes.

#### *Estimation of Threshold of Fundamental Frequency Difference Limen of Complex Tones*

The result of each participant in the two blocks was analyzed individually. If there were four out of the eight reversals larger than 76.8 Hz, the data would be excluded from the study. Since in the practice, the step size of each trial was fixed to 45 Hz, anyone who passed the practice should have the threshold lower than 76.8 Hz. If they got more than half number of reversals of 76.8 Hz, then the results were not likely to be reliable or valid. By the observation during data collection, children aged 3 and 4 had spent a long time before passing the practice, and they might have lose their attention on the experimental session after the practice. Another possible point of explanation was that in the practice, when the first and second intervals were the same, the same picture of a 'puppy' would be presented twice, together with the presentation of the first and second intervals. Otherwise, different 'puppies' were shown along with the first and second intervals respectively. Therefore, some children might have passed the practice by image-matching rather than responding to the tones they heard. In the experimental session, presentation of images was, however, different from those in practice. Therefore, the children who passed the practice session relying on image-matching could no longer achieve the test. To ensure the reliability and validity of the

data used, only the data showing a consistent response pattern of a participant would be used.


In the current experiment, the criterion to determine the consistency of the data was a set of four consecutive reversal points within three step sizes. As a result, the threshold of  $F0$  DLC for each participant was calculated by taking the mean of four consecutive reversal points within plus or minus ( $\pm$ ) three step sizes which the mean threshold value was the smallest.

Table 1

*An Example on Determination of the Mean Threshold of  $F0$  DLC from a Participant's Raw*

*Data*

Reversal	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	7 <sup>th</sup>	8 <sup>th</sup>
$F0$ DLC(Hz)	2.4	4.8	<b>2.4</b>	<b>4.8</b>	<b>1.2</b>	<b>2.4</b>	0.15	0.3



the four reversals taken to calculate the mean threshold of  $F0$  DLC ( $F0$  DLC = 2.7 Hz)

Table 1 showed an example for determining the  $F0$  DLC threshold. Referring to Table 1, although the last four consecutive reversals gave the smallest mean value, they were not within  $\pm$  three step sizes. The third to sixth reversal points were taken for determining the mean  $F0$  DLC threshold because the calculated mean value was the smallest among the means of any other four-consecutive-reversals within  $\pm$  three step sizes.



### *Reliability Measure*

Half of the participants in each group were randomly selected to take the same test two weeks after the first attempt of the test. The correlation between the means of each individual obtained in the test and retest under the 250 and 120 Hz *F0* conditions was evaluated using Pearson Product-Moment Correlation Coefficient *r*.

### Results

Ten out of twenty-one (48%) children in the 3-year-old group and ten out of fifteen (67%) children in the 4-year-old group completed the current study. Seven aged 3 and two aged 4 children failed to pass the practice session as they could not produce seven consecutive correct responses with the tones with large *F0* difference. Four additional 3-year-old and three additional 4-year-old children passed the practice session, but were discharged from the study because they were found to have more than four 76.8 Hz thresholds in their eight reversals. All participants in group aged 5 or above passed the practice session and completed the test session. All of their responses passed the criteria and were included in later data analysis.

There were two aged 3 and one adult participants did not produce four consecutive reversal points within three step sizes (one age-3 at the block of 120 Hz *F0*, another age-3 and one adult at the block of 250 Hz *F0* experiment). A more relaxed criterion for determining the threshold was employed to include their data into the analysis. The criterion

was using three consecutive reversals within  $\pm$  three step sizes with lowest mean value plus an adjacent lower reversal point in order to compute their mean  $F0$  DLC thresholds. Table 2 showed how the three participants' mean  $F0$  DLCs were computed. The highlighted four reversals were those used to calculate their mean thresholds.

Table 2

*The Computed Mean  $F0$  DLCs by a Relaxed Criterion for the Three Participants*

Participant (age / at block)	Participant's $F0$ DLCs (Hz) at reversal								Mean $F0$ DLC (Hz)
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	7 <sup>th</sup>	8 <sup>th</sup>	
3 / 120 Hz $F0$	<b>1.2</b>	<b>2.4</b>	<b>1.2</b>	<b>19.2</b>	4.8	9.6	0.6	76.8	6
3 / 250 Hz $F0$	0.3	4.8	<b>2.4</b>	<b>38.4</b>	<b>19.2</b>	<b>38.4</b>	2.4	4.8	24.6
Adult / 250 Hz $F0$	2.4	4.8	<b>0.15</b>	<b>0.6</b>	<b>0.15</b>	<b>2.4</b>	1.2	4.8	0.825

The means of the thresholds, the standard deviations ( $SD$ ) and the ranges of  $F0$  DLCs across each age group at 120 and 250 Hz  $F0$  are summarized in Table 3. The largest mean thresholds at 120 and 250 Hz  $F0$  conditions were found in the 3-year-old group. The mean thresholds decreased generally with increasing age. The lowest mean thresholds were found in the adult-group. Standard deviation and the range were found to be the largest in the

3-year-old group. The standard deviation and the range at 120 and 250 Hz  $F0$  conditions gradually decreased with increasing age and were the lowest in the adult-group.

Table 3

*Means, Standard Deviations and Ranges of  $F0$  DLCs at 120 and 250 Hz  $F0$*

Condition	$F0 = 120\text{Hz}$					
Age	3	4	5	6	10	Adult
Mean (Hz)	15.66	5.73	5.66	3.51	2.82	1.46
SD (Hz)	13.07	3.61	3.48	0.83	2.53	0.75
Range (Hz)	2.40 - 38.40	2.25 - 12.00	1.80 - 12.00	1.80 - 5.10	0.83 - 3.90	0.41 - 2.70
Condition	$F0 = 250\text{Hz}$					
Age	3	4	5	6	10	Adult
Mean (Hz)	17.04	6.57	5.99	4.22	4.13	2.17
SD (Hz)	9.98	4.06	4.59	1.67	1.58	1.34
Range (Hz)	7.20 - 36.00	2.70 - 16.80	1.20 - 18.00	1.80 - 7.20	2.25 - 6.60	0.28 - 3.60

Two-way repeated measures analysis of variance (ANOVA) was used to analyze the data. The research design involved two experimental variables: one within subject ( $F0$ ) and one between subjects (age). With reference to Table 3, the thresholds of the age-3 group were much higher than the other age groups. The variances at 120 and 250 Hz  $F0$  for age-3 group

were more than four times larger than those of other age groups and so the assumption of homogeneity of variances for ANOVA to be valid was violated. Also, only 52% of the age-3 participants completed the test. The high rejection rate indicated that the current age-3 sample could not well represent the whole age-3 population. Considering the high rejection rate, the much larger variances and much higher thresholds, data of the age-3 group was analyzed separately from other groups. Therefore, the following ANOVA compared only the data of age-4 or above groups. Interaction effect between age and  $F0$  was not significant,  $F(4,45)$ ,  $p = .98$ . Therefore, there was no significant effect of the combination of the two factors. Significant main effect was found for age,  $F(4,45)$ ,  $p = .0003$ . Post-hoc comparison Tukey HSD test revealed that significant differences occurred between (i) age-4 children and adult ( $p < .05$ ); (ii) age-5 children and adult ( $p < .05$ ). No significant main effect of  $F0$  was found,  $F(4,45) = 4.85$ ,  $p = .11$ . Therefore, the  $F0$  DLC thresholds obtained in the current study insignificantly depended on the effect of  $F0$ .

As mentioned, the data of the age-3 group was analyzed separately from the above repeated measures ANOVA. Firstly, matched  $t$ -test was used to analyze the effect of  $F0$  on the age-3 group. No significant difference was found,  $t(9) = .35$ ,  $p = .74$ . Therefore, the  $F0$  DLC threshold in aged 3 group at 120 Hz  $F0$  did not differ significantly from the threshold at 250 Hz  $F0$ . Secondly, the threshold of age-3 at 250 Hz  $F0$  was compared with that of age-4 by using non-parametric Mann-Whitney  $U$ -test. Significant difference was found,  $U = 9.00$ ,

$p = .002$ . The same  $U$ -test was used to compare the threshold of aged 3 at 120 Hz  $F0$  with that of aged 4. Significant difference was found,  $U = 22.50$ ,  $p = .04$ .

Five participants in each age group were randomly selected to undertake the test again two weeks after the first attempt of the test to check for the test-retest reliability. They all passed the practice session on the day of the second attempt. The performance of two out of five age-3 participants in the retest did not meet the criteria for being considered as valid. Thus, only the scores of the remaining three age-3 children in the retest were used in analysis for testing test-retest reliability. Pearson Product-Moment Correlation Coefficient  $r$  was used to evaluate the test-retest reliability for both conditions of 120 and 250 Hz  $F0$ . The  $F0$  DLC thresholds obtained in the test and retest session were not significantly correlated,  $r = .20$ ,  $p > .05$  (two-tailed), under the 120 Hz  $F0$  condition, while the  $F0$  DLC thresholds obtained in the retest was significantly positively correlated,  $r = .72$ ,  $p < .05$  (two-tailed), with the thresholds obtained in test under the condition of 250 Hz  $F0$ .

### Discussion

The results of the current study indicated that: (a) overall  $F0$  discrimination thresholds did not reach adult level until after 5 years of age; (b)  $F0$  discrimination thresholds at both 120 and 250 Hz of children reached adult level after aged 4, when investigating the  $F0$  DLC thresholds separately according to the  $F0$ . It was obviously improving from aged 3 to 4 since aged 3 children had a significantly higher threshold than that of aged 4 or above; (c)  $F0$

discrimination thresholds at 120 Hz was not significantly different from that at 250 Hz; and (d) the test-retest reliability of the test was fairly high under 250 Hz *F0* condition but was low under 120 Hz *F0* condition.

Finding (a) indicated there was an improving overall *F0* discrimination ability from aged 3 to 5 and the discrimination ability was adult-like after about 5 years of age. This result supported the first hypothesis raised in the introduction that a decreasing *F0* DLC was found with increasing ages. The ages for the *F0* discrimination ability reaching adult level differed by one year of age in finding (a) and (b). The difference might probably come from the large variability of the small sample size (*N*). A relatively extreme data at a particular age group under 120 or 250 Hz *F0* might cause a significant difference between the calculation of the mean *F0* DLC threshold of the age group separately relative to the *F0* (the situation of finding b) and by combining and averaging the thresholds obtained from the two *F0*s (the situation of finding a).

Thompson et al. (1999) showed that children's ability to discriminate pure tone frequency changes did not reach adult level until after 7 years old. Comparing their result with finding (a), the current result showed an earlier plateau of the developmental improvement on overall sensitivity. However, the finding by Thompson et al. was based on pure tone frequency discrimination while ours focused on complex tone *F0* discrimination. This might indicate that the maturation of the children's ability on complex tone *F0*

discrimination is earlier than that on pure tone frequency discrimination. The differences might also come from method used in getting the mean thresholds. In Thompson et al., the participants' task was to indicate which interval out of two intervals was 'different' while the participants' task in the current study was to indicate whether the two intervals were 'the same or different'. The current task reduced the demand on memory of the participants.

Different demands on cognitive abilities (e.g. memory) might play an important role in determining the performance of the younger participants as their cognitive abilities are still developing. The small  $N$  might also affect the sensitivity of the current study, leading to the result that apparently showing no differences found for the aged 4 or above groups under both 120 and 250 Hz  $F0$ .

In the introduction, hypothesis that a lower threshold would be obtained at lower  $F0$  was raised. Statistical analysis showed that the performances of participants at 120 and 250 Hz  $F0$  were not significantly different. Thus, there were no evidences to reject the null hypothesis. However, referring to Table 3, the means under 250 Hz  $F0$  was consistently higher than those under 120 Hz  $F0$ . One possible reason to explain the failure to reject the null hypothesis was due to the small  $N$  and also the large individual variability, causing the low sensitivity of the statistical tests.

### *Factors Affecting the F0 DLCs*

Large individual differences were observed in age group of 3 to 5 years old. In Jensen & Neff (1993), large individual differences of performances on frequency discrimination by his subjects aged 4, 5, 6 and adults were also observed. They emphasized that besides normal individual differences of abilities, differential development of basic auditory abilities and cognitive abilities should also be taken into consideration. D. V. M. Bishop, Carlyon, Deeks, and S. J. Bishop (1999) pointed out that poor attention, failure to adapt to specific task demands and slow learning of a new task would affect auditory processing. The immature cognitive abilities might also explain why about half of the age-3 and age-4 participants were excluded in data analysis, due to either the failure to pass the practice session or the failure to give consistent thresholds.

Training in Thompson et al. (1999) included two stages. The first stage involved three subsets of training, differing by the size of frequency difference. The participants were required to produce five consecutive correct responses in each subset. The second stage included training which required the participants to discriminate gradually smaller frequency differences until eight reversals were obtained according to the psychophysical step procedure. Thompson et al. found a larger frequency DL of their adult subjects (4.8 Hz) when compared with those from Turner & Nelson (1982) and Weir et al. (1977) (both found frequency DL smaller than 2 Hz). They explained that the difference might come from the



less extensive pre-training given in their study. They further elaborated that to obtain optimal performance levels of children, even more training than adults would be required. It was likely that complex tone *F0* discrimination might also be overestimated (i.e. underestimated children's sensitivity) if less training were given to participants. In the current study, less extensive training was given to the participants to avoid them getting exhausted and losing attention on the test. Both adults and children received more or less the same amount of training, depending on their performances in the practice session. The practice session included training trials from at least 7 to at most 20 trials, which was much even less extensive than Thompson et al.'s ones. The children's thresholds in the current study might, therefore, also be overestimated.

#### *Test-retest Reliability*

A fairly strong correlation in 250 Hz *F0* condition was found but no correlation was found in 120 Hz *F0* condition. Further research is necessary before concluding that the performances of the participants were reasonably consistent in the test and retest under 250 Hz *F0* condition but not under 120 Hz *F0* condition. It was because the inconsistent findings might be caused by the small amount of subjects and the large individual variations of them in the retest. Based on the current results, it was unlikely to conclude whether the current test was reliable to estimate the threshold of *F0* DLCs.

### *Clinical Implication*

The ability of processing sounds might be related to the specific learning impairment (SLI) (Bishop & McArthur, 2004). Cacace, McFarland, Ouimet, Schreiber, and Marro (1999) suggested that children with SLI might have specific auditory processing deficit. To understand if *F0* discrimination is one of the auditory processing areas which SLI children have deficits on, the current study could provide information for further investigation.

### *Directions for Further Research*

Limitations of the current study included small *N* and high rejection rate of the preschool children in completing the test. It was recommended that further research aiming to investigate preschool children auditory processing ability should recruit a larger amount of subjects.

With the small *N* and large variations of participants, the conclusion of whether the current test was reliable to estimate the threshold of *F0* DLCs could not be made. Further research are required to investigate if the *F0* discrimination ability of the participants are consistent under higher and lower *F0* conditions over a short duration of time.

There were no evidences found in the current study to support the hypothesis that children should have lower *F0* DLCs at lower *F0*. Moore (1995) suggested that for *F0* in the range of 100-400 Hz, changes as small as 0.2% in repetition rate of complex tones could be detected. In the current study, only *F0* of 120 and 250 Hz were compared. Further research

could examine if the hypothesis is true in comparing two complex tones with larger  $F0$  difference (e.g. 120 versus 350 Hz  $F0$ ); or to how large of the  $F0$  difference for the hypothesis to be true.

### Conclusion

The current study measured the  $F0$  discrimination threshold of complex tones for normally hearing preschool and school aged children and compared their thresholds with adults. Results showed that the  $F0$  discrimination ability at 120 and 250 Hz  $F0$  of children reached adult level after 4 years of age. No differences were found on the abilities of children and adult on discrimination for higher or lower  $F0$ . Further research is needed to justify the reliability of the test.

### Acknowledgement

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## Appendix A

*Consent Form for Adult Participants*

香港大學教育學院  
 言語及聽覺科學部  
 三至十歲香港兒童的頻率分辨能力之研究  
 同意書

本部將進行一項研究，目的為了解三至十歲兒童的頻率分辨能力。此項研究由本部副教授祝家華博士 (Dr Valter Ciocca) 帶領張明慧同學進行。

現誠邀閣下接受一次個別測試，需時大概二十分鐘。閣下會先接受一個簡單的聽力測試，以確聽力合乎是次研究標準。之後，測試員會把不同響聲播放出來，閣下會聽到兩個響聲，然判斷他聽到的兩個響聲是一樣或是不一樣。測試過程對閣下並沒有害處。而閣下的支持，將會有幫助我們了解香港兒童的聽覺能力與年齡成長的關係。

整個研究所獲得的資料只會作是次研究之用，並予以保密。在整個過程中，我們亦不會進行任何的錄影或錄音。

我們十分感謝閣下的支持及參與。如有任何疑問，請致電 93274876 與張明慧同學聯絡。

本人 \_\_\_\_\_ (中文正楷) 同意參與是項研究。茲證實上述所有事項，研究員已向本人詳細解釋，本人亦完全明白一切有關安排。

參加者簽署：

\_\_\_\_\_

聯絡電話：\_\_\_\_\_

日期：\_\_\_\_\_

研究員簽署：

\_\_\_\_\_

香港大學言語及聽覺科學部  
 四年級學生張明慧

日期：\_\_\_\_\_

## Appendix B

*Consent Form for Caregivers of the Children Participants*

香港大學教育學院  
 言語及聽覺科學部  
 三至十歲香港兒童的頻率分辨能力之研究  
 家長同意書

本部將進行一項研究，目的為了解三至十歲兒童的時間解析能力。此項研究由本部副教授祝家華博士 (Dr Valter Ciocca) 帶領張明慧同學進行。

現誠邀閣下兒子／女兒於二零零五年接受一次個別測試，需時大概二十分鐘。閣下兒子／女兒會先接受一個簡單的聽力測試，以確保貴子女之聽力合乎是次研究標準。之後，測試員會把不同響聲播放出來，貴子女會聽到一個或兩個響聲，而貴子女只需判斷他聽到一個或兩個響聲。測試過程對孩子並沒有害處。而閣下的支持，將會有幫助我們了解香港兒童的聽覺能力與年齡成長的關係。

整個研究所獲得的資料只會作是次研究之用，並予以保密。在整個過程中，我們亦不會進行任何的錄影或錄音。

我們十分感謝閣下的支持及參與。如有任何疑問，請致電 93274876 與張明慧同學聯絡。

本人 \_\_\_\_\_ (家長/監護人姓名) 同意 \_\_\_\_\_ (學生姓名) 參與是項研究。茲證實上述所有事項，研究員已向本人詳細解釋，本人亦完全明白一切有關安排。

家長/監護人簽署：

研究員簽署：

\_\_\_\_\_

\_\_\_\_\_

聯絡電話：\_\_\_\_\_

香港大學言語及聽覺科學部  
 四年級學生張明慧


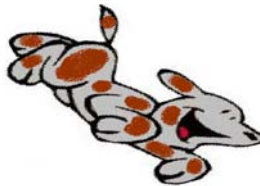




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## Appendix C







*The Sequence of the Auditory and Visual Presentation during Practice*

During the time of:	Screen content during a trial of the practice	
presentation of the first interval (e.g. a pair of low-to-high tones)		
presentation of the second interval (e.g. a pair of high-to-low tones)		
response time of the participant		
feedback		
	(shown after correct response was made)	(shown after incorrect response was made)

*Figure 1.* The sequence of the auditory and visual presentation during practice.

## Appendix D

*The Sequence of the Auditory and Visual Presentation during Experimental Session*

During the time of:	Screen content during a trial of experimental session	
presentation of the first interval (e.g. a pair of high-to-low tones)		
presentation of the second interval (e.g. a pair of high-to-low tones)		
response time of the participants		
feedback		
	(shown after correct response was made)	(shown after incorrect response was made)

*Figure 2.* The sequence of the auditory and visual presentation during experimental session.