The Dependence of Frequency Change Perception on the Acoustics of a Listening Environment and Its Implication for the Evaluation of Room Acoustics

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Abstract

Psychophysical approaches to the room acoustics have been made in number of researches. The present study is looking at whether the listener's perception of frequency change in rooms are dependent on the acoustics of a listening environment. P(C)s for frequency change in short tones were measured in different listening conditions. Two experiments were carried out to investigate the influence of room acoustics on the listener's perception of frequency change, and its implication for evaluating the acoustics of listening environments were examined and discussed. It was found that the temporal and spectral contents of reflections from room surfaces might be an important factor which influenced the listener's perception of frequency change in a reverberant sound field. This implicates that psychophysical approach by measuring listener's frequency change perception might be an useful tool for evaluating room acoustics. However, cares should be taken, since some individual differences were found to exist with respect to the direction of frequency change.

I. Introduction

Letowski [1] defined pitch as "the attribute of an auditory image that reflects the listener's impression of the location of the dominant spectral component along the frequency scale." Also, it is defined as "that attribute of auditory sensation in terms of which sounds may be ordered on a musical scale" [2]. Along with the perceived duration and loudness, pitch can be considered as an one-dimensional magnitude which corresponds to the change in frequency of a sound as well as a major contributor of timbre, hence musical quality heard in rooms as well as a major contributor to timbre, hence musical quality.

In a room, the sound from a source tends to be modified by the acoustic characteristics of the room, which implies that a listener, placed at a certain position in a room, will perceive the original sound as modified or coloured. By varying the acoustic conditions of a listening environment or simply changing the listening positions in a room, small but significant differences can be made in the frequency spectrum and time history of the sound. Bilsen [3,4] introduced the concept of repetition pitch and explained it as a pitch sensation that occurs when a sound reaches the listener's ear together with the delayed repetition of the sound. When the phenomenon occurs due to reflections in rooms, studios or concert halls, it has a significant influence, appreciated or not, on the perceived quality of speech and music [5].

The study of aural responses to transient tones is necessary for understanding the perception of speech and musical sounds which involve continuous changes in amplitude and frequency. As to frequency change, in particular, it is well known that a tone, with a large and gradual change in frequency, conveys a clear impression of pitch change. This change may have a significant influence on the quality of a heard tone, as well as in the application of musical expression. The transition in formant frequency of speech, in practice, is said to be an important cue for the identification of a phoneme [6]. In musical sounds, especially in wind instrument tones, the frequency changes near the onset of a note were known to be one of the characteristic features of this kind of instrument [7, 8].

Based on these well-known important aspects of frequency change in rooms, a number of researches [9-13] have explored the influence of room acoustics on FM

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(frequency modulated) and AM (amplitude-modulated) sounds propagating in listening environments. These studies were mainly concerned with how room transmission characteristics physically affect AM and FM sounds [14] and its applicability to assess the acoustics of listening environments for music and speech. In those works, changes introduced by the acoustic condition of a listening environment in the frequency domain of swept tones were monitored and analyzed. However, whether those changes by the acoustics of a room in the frequency domain of swept tones were perceivable for listeners has not been thoroughly investigated.

The hypothesis under investigation is that the acoustics of the listening environment affects the listener's perception of frequency change in short tones. By varying the acoustic conditions of a listening environment, small but significant differences can be made in the frequency spectrum and envelope shape. Also, those changes perceived by listeners are expected to reflect the acoustic properties of the listening environment. For room acoustics, the threshold of perceptibility of pitch and timbre is also a threshold of perceptibility of colouration (of an original sound due to the addition of reflections), since no other qualities than pitch and timbre form part of the notion of colouration [4].

Two experiments were carried out to investigate the influence of room acoustics on the listener's perception of frequency change, and its implication for evaluating the acoustics of listening environments were examined and discussed.

Ⅱ. The dependence of the perception of frequency change on the reverberation time of a listening environment

Two different models (place model and temporal information model) have been developed to explain the mechanism of pitch perception. The Zwicker model [15], which is one of the major place model theories, explains the pitch perception as the result of changes in the excitation patterns elicited by the stimulus when the frequency is altered. This suggests that the sharper the tuning of peripheral filtering mechanisms, the smaller should be the frequency difference limens (DLFs). However, following efforts by other researchers [16-19] found that the place model can only be applied to frequencies above 5kHz, and DLFs are determined by temporal information (phase locking; the tendency for nerve firings to occur at a particular phase of the stimulating waveform on the basilar membrane) for frequencies up to 4 ~ 5kHz. Also, Attneave and Olson [20] showed that an abrupt breakpoint exists at about 5kHz for the clear perception of the musical interval of an octave. As an alternative to the place theory, the temporal theory suggests that the pitch of a stimulus is related to the time pattern of the neural impulses evoked by that stimulus. It appears that only pure tones below 5kHz have a pitch in the sense that a sequence of tones can evoke a sense of musical interval or melody [21]. It is therefore appropriate to restrict the frequency range, in the present study, to a maximum of 4kHz to avoid any conflict caused by the different mechanisms of frequency perception.

The present section investigates a listener's ability to detect a frequency change in given swept tone in both an anechoic listening condition and a normal listening environment. An experiment was carried out in a lecture room and an anechoic chamber at the University of Sydney. A listener's perception of the frequency change was investigated through the experimental paradigm based on the signal detection theory [22, 23]. Two stimulus duration cases (110 and 210ms) and two frequency change directions (ascending and descending) were examined at three frequencies (0.25, 1, and 4kHz). P(C)'s measured at two different listening positions in a lecture room are compared and discussed.

2.1. Stimuli

Stimuli, with linear frequency changes from their onsets to offsets, were generated using a function generator (Philips Function Generator, PM 513). In the present experiment, stimuli had frequencies of 0.25, 1 and 4 kHz. The duration of the stimuli were 110 ms for short duration stimuli and 210ms for long duration stimuli including onset and offset intervals. To minimise switching transients at the onset and offset of the signals, the signals were linearly ramped up and down over 5ms. The duration of the frequency change (transition), usually observed in speech, is in the range 10-100 ms, and in musical sounds the transition duration near the onset is less than 100 ms [24]. No steady state was provided around the transition area (In speech, the formant transition is either preceded or followed by a steady state, in the form of vowel [25]).

Three different frequency change patterns (unmodulated steady tone bursts, ascending linear frequency changes, descending linear frequency changes) were used for the stimuli (see Fig. 1.). Standard stimuli always have a constant frequency from the onset to the offset, while comparison stimuli have either ascending or descending frequency change. Those different change patterns were randomly distributed throughout the experiment and presented to the listener. The priori probability (the probability of each stimuli, presented to the listener, to appear in an experiment) of each pattern was not known to the listeners, since it might cause biased responses based on the known prior probability.

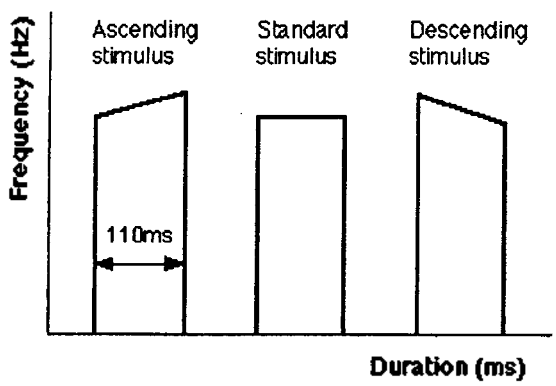


Figure 1. Time-frequency plots of stimuli used in the present experiment.

The listening level of stimuli at the listening position was kept constant at 77dB(A) [26] when measured with a single 1/2 inch free-field microphone (B&K, Type 4190). Frequency change ratios ((F/F) for each frequency were chosen based on a pilot test. Through a preliminary test, the JNDs of frequency change were obtained from each listener for both 110ms and 210ms duration signals using headphones. Frequency change ratios ((F/F) used in this experiment were decided roughly around the mean

Table 1. The adopted frequency change ratios ((F/F) for each frequency.

Frequency (Hz)	Used stimuli pairs (ΔF/F)	
	Short duration (110ms)	Long duration (210ms)
250	0.02 (5Hz)	0.008 (2Hz) 0.02 (5Hz)
1000	0.012 (12Hz) 0.016 (16Hz)	0.12 (12Hz)
4000	0.0075 (30Hz) 0.01 (40Hz)	0.005 (20Hz) 0.0075 (30Hz)

difference limen of both listeners, since each listener may have different ability in detecting a frequency change. The frequency intervals between the initial frequency and the terminal one are harmonically unrelated (Table 1).

2.2. Listeners

Two male postgraduate students voluntarily participated in this experiment. Both listeners are in their early 30's. One of the listeners (DC) had a musical background (BMus.) and the other listener (DU) had previously taken part in other auditory experiments. Neither of the listeners had a known hearing deficiency.

2.3. Experimental arrangement and procedure

The experiment was controlled by a PowerPC AV. The stimuli were generated by a function generator (Philips Function Generator, PM 513). The generated stimuli were recorded as 16 bit sounds (at a sampling rate of 44.1 kHz) and edited using an application, SoundEdit16, and saved in a range of file formats on the computer hard-disk. A program was written under the environment of PsyScope [27] for the presentation of stimuli and collecting responses.

The processed stimuli were amplified (YAMAHA Integrated Stereo Amplifier) and presented through a single loudspeaker (JVC 4WAY Loudspeaker). The loudspeaker was installed on the centre line of the room, 2 m from the front wall, and 1.5m from the floor. Two listening positions, in a lecture room, were randomly chosen. One position (P1) was on the centre line of the room, 5m distant from the source and the other position (P2) was selected at the right side of the room by keeping the distance from the source same as the other position (Fig. 2.). In the anechoic chamber, only one listening position was chosen. A loudspeaker was installed on the centre line of the anechoic chamber, 1 m from the front wall, and 1.5m from the floor. The discrepancy between the distance in the two listening environments was compensated by keeping the listening level equal.

A computer keyboard and a monitor were provided to the listener for processing the experiment and collecting responses. The listener was seated at each position and asked to respond by pressing the computer keyboard keys. Listeners were asked to face the source, but no physical restraint was placed on the head movement.

Listeners were presented with a single stimulus at each trial and were asked to determine whether there was a frequency change in the heard sound or not. The interval between trials and the response interval were not fixed and enough time was given for listeners to make their decision. The next trial started only when the listener inputed his response by pressing a keyboard button. Each response initiated the next trial after a 0.5s pause. No feedback concerning the accuracy of their responses was provided to listeners. Each stimulus was presented 16 times and the order of the ascending and descending stimuli was randomly distributed throughout the experiment. Also, the order of frequency ranges presented in each session was randomised. A two hours of practice session was provided to each listener before the main test. Each listener served two hours a day and completed the experiment over three days.

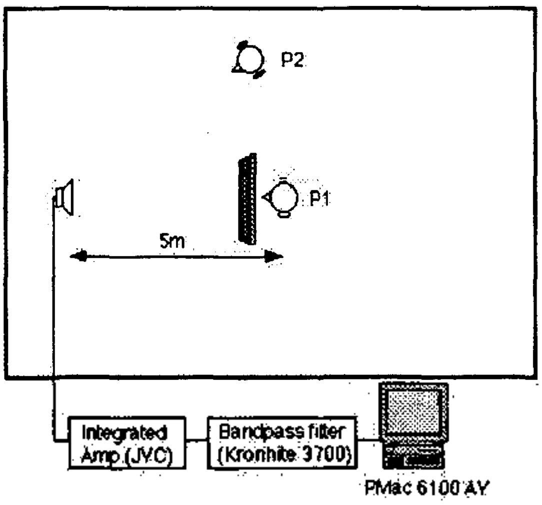


Figure 2. The experimental arrangement in the lecture room.

2.4. Data analysis

In the present work, three different frequency change patterns (unmodulated steady tone bursts, ascending linear frequency sweeps, descending linear frequency sweeps) were used for the stimuli. Also, one or two fixed frequency change ratios ((F/F) for each frequency were applied to the stimuli throughout the experiments. The emphasis of this study was placed on comparing the influence of different rooms based on the listener's performance over a particular frequency change ratio in those listening environments, rather than measuring the difference limens by psychometric function. Therefore the notion of percentage correct response [P(C)] was adopted instead of the detectability (d'). P(C)s were calculated from the priori probability of frequency change [P(SN)], the priori probability of unmodulated steady tone bursts [P(N)], the hit rate (P(y|SN)), and the rate of correct rejection (P(n|N)) based on the signal detection theory. The following equation, suggested by Robinson and Watson [28] was used to calculate the P(C);
where,

$$P(C) = P(SN)\cdot P(y\,|\,SN) + P(N)\cdot P(n\,|\,N) \qquad (1)$$

P (SN) : The probability of frequency change tones are presented

P (N) : The probability of non frequency change tones are presented

P (y|SN) : Hit rate, the frequency change is present and the listener says "yes"

P (n|N) : Correct rejection, the frequency change is absent and the listener says "no"

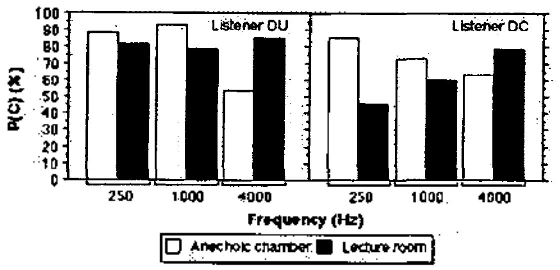
2.5. Results and discussion

A listener's perception of frequency change was measured for short and long duration stimuli in two different listening environments, at three different frequencies (0.25k, 1k, and 4kHz). Fig. 3. presents the P(C)s measured for the two duration cases in different rooms.

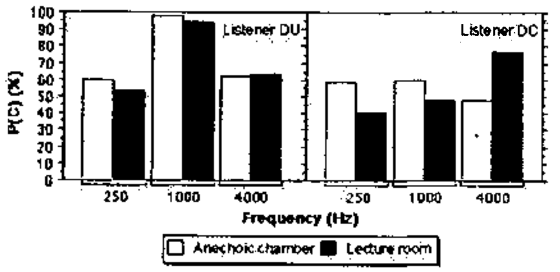
Both listeners showed higher detectability of frequency change for short duration tones in the anechoic chamber for low and mid-frequencies. However the lecture room was found to be the better listening environment for the frequency change detection at 4kHz. Clear differences were observed at 4 kHz in the lecture room. Both listeners showed better performance in a lecture room at 4kHz and the differences in P(C)s were up to 30%, which suggests that there might be a significant effect of the listening environment on the listener's frequency change perception. However, the effect of listening environment on the frequency change perception seems to be diluted when the longer duration stimuli were used. The observed influence of listening environment on the P(C)s of listener DU was less than 5% when the longer duration stimuli were employed. For the listener DC, P(C)s at low- and mid-frequencies were influenced by increasing the duration of the stimuli, while a slight decrease was observed for high frequency. The findings suggest that the short duration might be more useful for showing the influence of a listening environment on the frequency change perception. Fig. 4. shows the average P(C)s with standard errors from two listeners, measured at two different listening positions in the lecture room, for three frequencies. No significant difference was found in the P(C)s between the listening position P1 and P2 at 0.25k and 1kHz. A small but significant difference was found at 4kHz. The observed difference at the high frequency might be due to the different acoustic condition of each listening position. However, it is possible that the other experimental factors, such as listener' s head movement, source directivity and other factors, not controlled in the experiment might have influenced the results.

Fig. 5. shows P(C)s for two different frequency change directions. Listener DC showed a consistent trend in both the lecture room and the anechoic chamber regardless of the direction of frequency change (ascending or descending), while a discrepancy was found for the P(C)s of listener DU at 1kHz. Listener DU showed a similar trend at 0.25k and 4kHz in both rooms while contradictory results were found at 1kHz. Also listener DC' s performance was found to be significantly influenced by the direction of frequency change, in spite of a similar trend for both frequency change directions. Both listeners showed consistency for the ascending frequency change.

These results may be caused by the individual differences in sensitivity or preference for a specific direction of frequency change. Tsumura et al, [24] reported the consistency between listeners using a swept signal which is surrounded by steady states. Gardner and Wilson [29] suggested the existence, in the auditory system, of channels specific to upward FM and downward FM in a frequency change detection experiment using upward and downward sweeping signals. Dooley and Moore [17,18] found discrepancies between listeners, and argued that such discrepancies were caused by the differences in stimuli. They didn' t use the stimuli surrounded by the steady states. The stimuli in this experiment also had no such steady state and the result from this research is comparable with Dooley and Moore' s.



(a) Short duration (110ms)



(b) Long duration (210ms)

Figure 3. The frequency change perception, for two duration cases, measured in different listening environments.

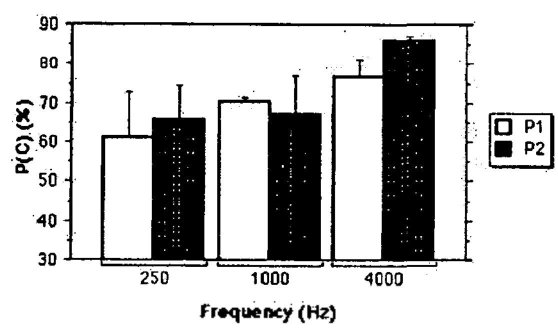
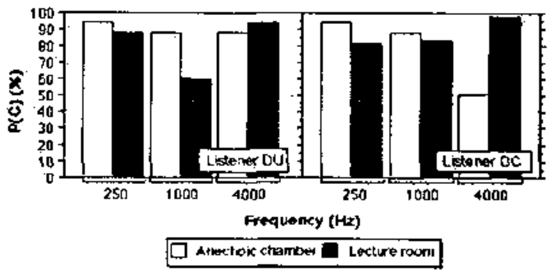
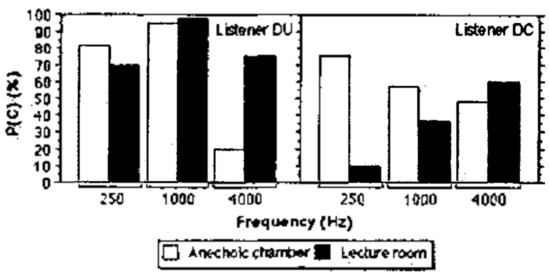


Figure 4. The dependence of frequency change perception on the listening position in the lecture room (the error bars shows (standard errors).



(a) ascending frequency change



(b) descending frequency change

Figure 5. The frequency change perception and the direction of change in different listening environments.

It seems there exists no obvious explanation other than individual differences.

Ⅲ. The perceived frequency change in a reverberant room

In the present section, an experiment was reported on the listener' s perception of frequency change, as a function of the distance from the source and listening position in a reverberant room. The experiment was carried out using a dummy head and an omni-directional source setup.

Three listening positions were selected by simply doubling the distance from the source to the listening position. The present experiment investigated whether the listening level was a determinant variable in the frequency change perception in a reverberant room. Two different conditions (Source Level Controlled; SLC and Listening Level controlled; LLC) were considered. The source level was always kept constant in the SLC condition, while the listening level at each listening position was controlled to be the same in the LLC controlled. Also, the effect of the frequency change direction on the listener' s performance was investigated again in an anechoic chamber using a dummy head and loudspeaker setup. Three different types of stimuli (unmodulated steady tones, ascending linear frequency sweeps, and descending linear frequency sweeps) were investigated. The two questions addressed were as follows;

1) Does the distance from the source to listener influence the frequency change perception in a reverberant room? If it does, is it caused by the listening level difference?

2) Is there any specific direction of frequency change, which listeners feel comfortable with?

Brief tones at 1kHz with a fixed frequency change ratio, were used for investigating the effect of distance from the source and listening level in a reverberant room. The stimuli were produced and recorded in a reverberation chamber using a loudspeaker and dummy head setup. The recorded sounds were reproduced for the listeners through headphones and the listener' s P(C)s were measured through the experimental paradigm based on a signal detection theory [22,23]. In an anechoic chamber, the measurement was carried out at one listening position, using the same experimental setup as in the reverberation chamber, to find out the listener' s sensitivity to the direction of frequency change. JNDs of frequency change were measured for both ascending and descending frequency changes. The listener' s task was to determine whether there is a frequency change heard.

3.1. Stimuli

For investigating the effect of distance from the source on the frequency change perception, the frequency change ratio ((F/F) of 0.016 (equivalent to 16 Hz/s linear frequency change from the onset to the offset), with ascending frequency change, was used. The frequency change always started from 1 kHz and ended at 1016 Hz (terminal frequency) and the steady tone bursts had a constant frequency of 1 kHz. The duration of the signal used in this test was 110ms. To minimise switching transients at the onset and offset of the signals, rise/decay times of 5 ms were used.

3.2. Listeners

Four female undergraduate students from the University of Sydney participated in this experiment. One (JH) of the listeners was an amateur musician (B.Mus), and two listeners (MK and LIN) also had a background as amateur music performers (AMEB Grade 7). The listener JE was a naive listener. They ranged in age from 18 to 23. They had previous experience in other auditory perception experiment. Listeners were paid by hourly rate. None of the listeners were known to have hearing deficiencies.

3.3. Experimental arrangement and procedure

The swept tones, generated by a function generator (Philips Function Generator PM 513), were played in the reverberation chamber and anechoic chamber through a loudspeaker (JVC 4WAY Loudspeaker). The generated stimuli were binaurally recorded as 16 bit sounds (at a sampling rate of 44.1 kHz) by a digital audio tape recorder (SONY, PCM-2700A) through a dummy head (NEUMANN, KU100). The recorded stimuli were edited using an application, SoundEdit16, and saved in a range of file formats on the computer hard-disk. The processed stimuli were amplified (JVC Integrated Stereo Amplifier) and presented through headphones (TDH 49P). The experiment was controlled by a PowerMacintosh AV. A program, written under the environment of PsyScope [27], was used for the presentation of stimuli and response collecting.

Three different positions were chosen by simply doubling the distance from the source to the listener along the center line of the source. A loudspeaker was installed on the longitudinal axis of the room and 1m from the rear wall (Fig. 6.). The center of the source and the position of the dummy head ear was placed at the height of 1.2m from the floor. At each position, two different listening conditions (SLC and LLC condition) were applied. In SLC condition, source level was fixed at 77dB when measured at 1m from the source. In the LLC condition, the listening level at each position was controlled to be same (77dBA), when measured at each listening position with a single 1/2 inch free-field microphone (B&K Type 4190).

The interval between trials was not fixed and enough time was given to listeners to make their decisions. The next trial was always initiated after 1s by the response of a listener to the previous pair of stimuli. A daily test was composed of three different sessions. All the stimuli were presented 10 times in each session and the order of the ascending and steady tone burst stimuli was randomly distributed. Before the main test, a two hour training session was given to each listener and the P(C) for the frequency change ratio ((F/F) of 0.016 was measured at the end of the practice session. Each listener undertook 1.5 hours of testing a day and completed the experiment over three days.

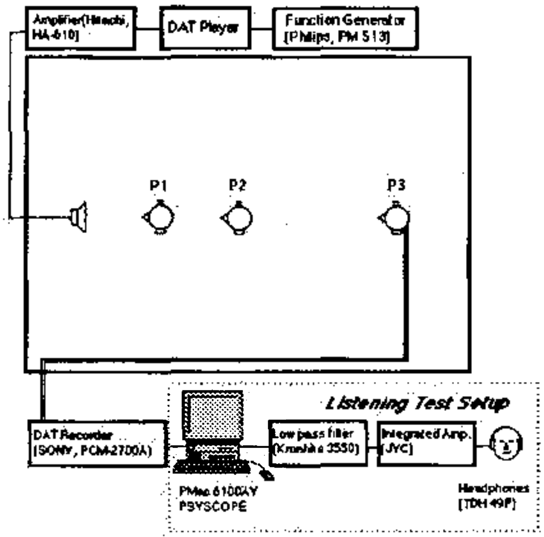


Figure. 6. The schematic diagram of the experimental setup in the reverberation chamber. The effects of the distance from the source to listener were investigated.

During the assessments listeners were seated in the quiet room, and a computer keyboard and monitor were provided for presenting stimuli and collecting responses. The listener' s task was simply to determine whether there was a frequency change in a heard sound, presented through headphones. No feedback was provided to the listeners.

3.4. Results and discussion

Fig. 7. presents listener' s JNDs, measured for two different directions of frequency change in an anechoic condition. The result clearly shows that listeners, involved in the present experiment, are more sensitive to the direction of ascending frequency change.

The average JNDs of listeners for ascending frequency change was found to exist within 11-16Hz, while the average JNDs for descending frequency change ranged from 17 to 23Hz. Also, larger error bars were obtained for descending frequency changes which suggests that listener' s frequency change perception may be less stable for the descending frequency changes. A t-test confirmed that a significant difference exists between JNDs for the ascending and descending frequency change at the significance level of $p<0.0001$.

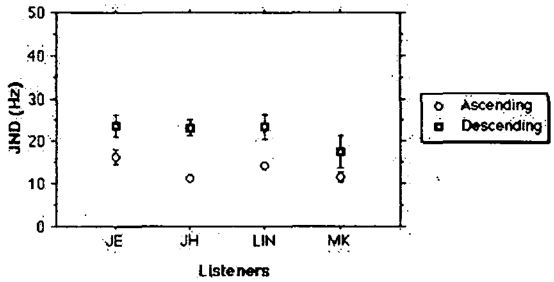


Figure 7. Measured JNDs for the ascending and descending frequency change (at the frequency change ratio ((F/F) of 0.016) in an anechoic condition (Error bars show ± standard errors).

The percentage of correct responses [P(C)s] were determined, in the second experiment, as a function of the distance from the source to the listener. Two different conditions were applied, in one of which the source level was kept constant (SLC condition) and, in the other, the listening level was kept constant (LLC condition) regardless of the distance from the source. The equation (1) in section 2.4. was used to calculate the P(C)s. The measured mean P(C)s from four listeners were plotted with error bars in Fig. 8., as a function of distance from the source to the listener.

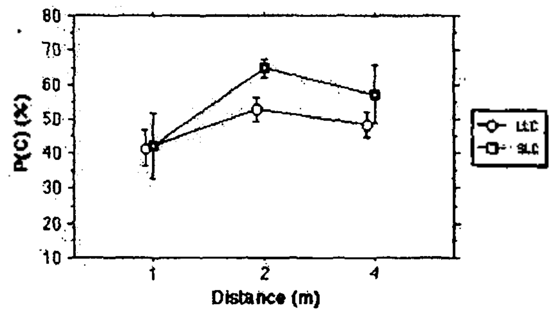


Figure 8. The effect of distance on frequency change perception under two different conditions (SLC and LLC condition) in a reverberant room (The error bars show ±standard errors).

Under the listening condition of SLC, every listener showed the highest P(C)s at the listening position P2. A quite similar trend was observed when the listening level was kept constant. The differences in P(C)s between P1 and P2 were found to be significant for both SLC and LLC listening conditions by a t-test ($p<0.05$). No significant difference was found between P2 and P3.

It is known that the binaural diplacusis causes additional systematic pitch shifts in a binaural listening condition [32]. In real listening environments there always exist phase and intensity differences between two ears. The phase shifts occurring in the reverberant sound field are so unsystematic that they can be considered as random or quasi-random. Schorer [33] reported that the listener' s ear is less "phase sensitive" in a reverberant room than it is in an anechoic room and he concludes that phase differences between the partials are of minor significance for listening in a normal room. Recently, Kuttruff [34] reasserted that our hearing is virtually insensitive to phase relations in stationary or quasistationary sound signals presented in reverberation enclosures. Therefore, the influence of phase on the perception of frequency change can be thought of as minor. What, then, causes the difference in P(C)s at different distances from the source in a reverberant room? It is well known that the detectability of auditory stimuli improves in proportion to the intensity of stimuli. In the SLC condition, adopted in the present experiment, a certain amount of listening level difference would be introduced to each position by doubling the distance from the source because of the higher level, but this was not so. Even when the listening level at each position was controlled to be constant, a similar trend was still observed.

Henning [16] measured frequency difference limens (DLFs) for tones whose level was varied randomly from one stimulus to the next. The random variation in level produced changes in loudness which were large compared with those produced by the frequency changes. He found that DLFs at high frequencies (4 kHz and above) were markedly increased by the random variation in level, whereas those at low frequencies were not. Moore and Glasberg [18] also measured DLFs for tones whose level was randomised from one stimulus to the next, but they randomised the level over a relatively small range (6 dB) to minimise changes of pitch with level. They found the 6 dB range was still large relative to the changes in excitation level produced by small frequency changes. These results suggest that listener' s abilities to detect changes in frequency over time may be more dependent upon the variation in level over time (changes in amplitude envelope) rather than the overall listening level. Recently, Rutkowski [35] suggested that instantaneous pitch changes in a reverberant room may be dependent upon the reverberation time. In the present experiment, the effect of reverberation time on the frequency change perception should be insignificant, since the listening positions were chosen in a room. The level variation of a steady tone in a reverberant room is a complicated function of reflected sounds from room surfaces. It is likely that the observed differences in P(C)s between the listening positions were the effects of the room reflections which caused the variations in the amplitude envelope and spectral shape.

Those three listening positions were chosen outside of critical distance (approximately, 0.33m for the given listening condition).

Ⅳ. Implications and conclusions

The present work investigated the relationship between the acoustics of a listening environment and listener' s perception of frequency change. It was found that listener' s perception of frequency change was influenced by changing the listening positions in a room. Also, room reflections were found to contribute positively to the improvement of listener' s detectability of frequency change in a reverberant sound field. This implicates that psychophysical approach by measuring listener's frequency change perception might be an useful tool for evaluating room acoustics. However, cares should be taken, since some individual differences seemed to exist with respect to the direction of frequency change. Also, the limited number of listeners in the present study needs further collection of data from more listeners for the generalization of the result. It is likely that the observed variations in the listener's perception of frequency change was the influence of the temporal and spectral contents of reflections from room surfaces rather than a simple function of reverberation time of a sound field.

Obvious next steps in the current research are: (1) Determine the listener's perception in acoustically well-defined listening environments; and (2) Investigate their relationship with the subjectively assessed room acoustic quality.

References

1. Letowski, T., "Timbre, tone colour, and sound quality: concepts and definitions," Archives of Acoustics, Vol.17, pp.17-30, 1992.
2. American Standards Association, *Acoustical Terminology* S1, 1-1960, American Standards Association, New York, 1960.
3. Bilsen, F.A., "Thresholds of perception of repetition pitch. Conclusions concerning coloration in room acoustics and correlation in the hearing organ," Acustica, Vol.19, pp.7-32, 1968.
4. Bilsen, F.A. and Ritsma, R.J., "Some parameters influencing the perceptibility of pitch," *J. Acoust. Soc. Am.*, Vol.47, pp.469-475, 1970.
5. Sommerville, C.L.S., Gilford, N.F., and Negus, R.D.M., "Recent work on the effects of reflections in concert halls and music studios," *J. Sound Vib.*, Vol.3, pp.127-134, 1966.
6. Lieberman, A.M., Delattre, P.C., Gerstman, L.J., and Cooper, F.S., "Tempo of frequency change as a cue for distinguishing classes of speech sounds," *J. Exp. Psychol.* Vol. 52, pp. 127-137, 1956.
7. Freedman, M.D., "Analysis of musical instrument tones," *J. Acoust. Soc. Am.*, Vol.41, pp.793-806, 1967.
8. Luce, D. and Clark, M., "Physical correlates of brass instrument tones," *J. Acoust. Soc. Am.*, Vol.42, pp.1232-1243, 1967.
9. Ozimek, E., "Physical and psychoacoustic evaluation of FM signals propagating in a room," *Proceedings of 13th ICA*, pp.177-180, 1989.
10. Ozimek, E., and Sek, A., "AM and FM difference limens and their reference to amplitude-frequency changes of a sound in a room," Acta Acustica, Vol.82, pp.114-122, 1996.
11. Ozimek, E., and Rutkowski, L., "Deformation of frequency modulated (FM) signals propagating in a room," *Applied Acoustics*, Vol. 26, 217-230, 1989.
12. Rutkowski, L., and Ozimek, E., "Linear and jump frequency changes of a signal in a room," Archives of Acoustics, Vol. 20, No. 2, 115-138, 1995.
13. Rutkowski, L., and Ozimek, E., "Linear and sinusoidal frequency changes of a signal in a room," Acta Acustica, Vol. 83, 881-890, 1997.
14. Jeong, D.-U., and Fricke, F.R., "Frequency perception as a measure of room acoustic quality," *Applied Acoustics*, 1999 (to be published).
15. Zwicker, E., "Masking and psychological excitation as consequences of the ear's frequency analysis." In *Frequency analysis and periodicity detection in hearing* (eds. Plomp, R. and Smoorenburg, G.F.), Sijthoff, Leiden, 1970.
16. Henning, G.B., "Frequency discrimination of random amplitude tones," *J. Acoust. Soc. Am.*, Vol. 39, pp. 336-339, 1966.
17. Moore, B.C.J. and Glasberg, B.R., The role of frequency selectivity in the perception of loudness, pitch and time. In *Frequency selectivity in hearing* (Ed. Moore, B.C.J.), Academic Press, London and New York, 1986.
18. Moore, B.C.J. and Glasberg, B.R., "Mechanisms underlying the frequency discrimination of pulsed tones and the detection of frequency modulation," *J. Acoust. Soc. Am.*, Vol.86, pp.1722-1732, 1989.
19. Emmerich, D.S., Ellermeier, W., and Butensky, B., "A re-examination of the frequency discrimination of random amplitude tones, and a test of Henning's modified energy-detector model," *J. Acoust. Soc. Am.*, Vol.85, pp.1653-1659, 1989.
20. Attneave, F. and Olson, R.K., "Pitch as a medium: a new approach to psychophysical scaling," *Am. J. Psychol.*, Vol.84, pp.147-166, 1971.
21. Moore, B.C.J., *An introduction to the psychology of hearing*, Academic press, London, 1991.
22. Macmillan, N.A. and Creelman, C.D., *Detection*

Theory: A user's guide, Cambridge Univ. Press, 1991.

23. Green, D.M. and Swets, J.A., Signal detection theory and psychophysics, Kreiger, New York, 1974.
24. Tsumura, T., Sone, T., and Nimura, T., "Auditory detection of frequency transition," *J. Acoust. Soc. Am.*, Vol.53, pp.17-25, 1973.
25. Schouten, M.E.H., "Identification and discrimination of sweep tones," Percept & Psychophysics, Vol. 37, pp. 369-376, 1985.
26. Ando, Y., *Concert hall acoustics*, Springer-Verlag, Berlin, pp. 65-68, 1985.
27. Cohen J.D., MacWhinney B., Flatt M. and Provost, J., "PsyScope: A new graphic interactive environment for designing psychology experiments," Behavioural Research Methods, Instruments & Computers, Vol.25, pp. 257-271, 1993.
28. Robinson, D. E. and Watson, C. S., *Psycho-physical methods in modern Psychoacoustics, in Foundations of modern auditory theory*, edited by Tobias, J. V., Academic press, N.Y. and London, pp.122-124, 1972.
29. Gardner, R.B. and Wilson, J.P., "Evidence for direction-specific channels in the processing of frequency modulation," *J. Acoust. Soc. Am.*, Vol. 66, pp. 704-709, 1979.
30. Dooley, Gary J. and Moore, B.C.J., "Detection of linear frequency glides as a function of frequency and duration," *J. coust. Soc. Am.*, Vol.84, pp.2045-2057, 1988a.
31. Dooley, G.J. and Moore, B.C.J., "Duration discrimination of steady and gliding tones: A new method for estimating sensitivity to rate of change," *J. Acoust. Soc. Am.*, Vol. 84, pp. 1332-1337, 1988b.
32. Terhardt, E., "Pitch, consonance and harmony," J. *Acoust. Soc. Am.*, Vol. 55, pp. 1061-1069.
33. Schorer, E., "Critical modulation frequency based on detection of AM versus FM tones," *J. Acoust. Soc. Am.*, Vol. 79, pp. 1054-1057.
34. Kuttruff, H., "On the audibility of phase distortions in rooms and its significance for sound reproduction and digital simulation in room acoustics," *Acustica*, Vol. 74, pp. 3-7, 1991.
35. Rutkowski, L., "Room response to frequency change and its relation to the pitch change," *Archives of Acoustics*, Vol. 21, pp. 201-214, 1996.

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