Pitch-Intensity Dependence and its Implications for Pitch Perception

著者	MIYAZAKI KEN-ICHI
journal or publication title	Tohoku psychologica folia
volume	36
page range	75-88
year	1978-03-20
URL	http://hdl.handle.net/10097/00064926

Tohoku Psychologica Folia
1977, 36(1–4), 75–88

PITCH-INTENSITY DEPENDENCE AND ITS IMPLICATIONS FOR PITCH PERCEPTION

By

KEN-ICHI MIYAZAKI (宮崎謙一)

(Department of Psychology, Tohoku University, Sendai, Japan)

A series of experiment were performed to examine the pitch-intensity dependence. In experiment 1 which involved a pitch-matching task, a slight but systematic pitch-shift with intensity was found for pure-tones. However, in experiment 2 in which *S*s were required to make adjustment of relational pitch according to his musical interval sense, no systematic pitch-shift was obtained. It was concluded from these results that the extent of the pitch-shift depends upon the degree of the musical context involved in the situation. Pitch was defined as the musical characteristic inherent to the tone sensation and its meaning was restricted to the *musical pitch* differenciated from *timbre*. Then it could be mentioned that pitch does not change with intensity. Observed pitch-shift in a pitch-matching task was regarded as the nonmusical phenomenon and was largely due to the change in timbre rather than pitch. Related physiological evidences were also considered.

INTRODUCTION

The pitch of a tone stimulus primarily depends on its frequency. It is known, however, that pitch is also influenced to some extent by other secondary variables such as intensity, duration, and spectral composition of the sound stimulus. Of these variables the effect of intensity upon pitch was noticed by early investigators, and some quantitative measurements have been performed. One of the most commonly accepted is the study of Stevens (1935), which showed that the increase in intensity raised the pitch of high frequency pure-tones, lowered the pitch of low frequencies, but had negligible effects upon the pitch of middle frequencies, and that the extent of the pitch shift becomes greater as the frequency reached the high or low extreme region. These findings were summed up in a family of *equal-pitch contours* just as the well-established *equal-loudness contours*. These curves have been so frequently referred to that they could be regarded as the *Stevens' law* of the pitch-intensity relationship. However, Stevens' experiment contained several problems. First, the method used was to present successively two pure-tones of slightly different frequencies and to allow *S* to adjust the intensity of one instead of the frequency until its pitch got matched the other. This method seems to be unnatural and may cause more *artifacts* on pitch-intensity effects because variation of intensity can produce only slight pitch shift and therefore it should be extremely difficult for *S* to make a pitch matching by adjusting intensity. Secondly, it remains doubtful whether the *pitch-intensity law* Stevens formulated could be regarded as the representative results, because his experiment was based almost entirely on one *S*. Later investigators criticized Stevens' study mainly on these points. For instance, Ward (1970) mentioned that the pitch-intensity effect represents the results of an atypical observer operating in a rather unusual experimental setting, and Wever (1949) went to the extent of calling this effect of "*pitch-intensity illusion*". Neverthless, it might be acknowledged at least that the *Stevens' law* of the pitch-intensity relationship has been confirmed by some investigators only in terms of the general tendency of pitch shift that the pitch of a high-frequency pure-tone tends to rise and the pitch of a low-frequency pure-tone tends to lower as the intensity increases. However, in other respects there have been obtained a lot of results inconsistent with the *Stevens' law*. For example, Morgan et al. (1951), Nickerson (1951), and Cohen (1961) found the individual differences of pitch shift induced by the intensity change was so large that they could not detect a general tendency. Moreover, Verschuure et al. (1975) revealed that pitch shifts significantly as intensity changes but the functions of pitch shift take a non-monotonic shape in contrast to the monotonic functions Stevens found. On the other hand, there exists another evidence to support Stevens' findings up to a certain extent. For instance, Walliser (1969a) obtained similar functions of pitch shift to those of Stevens, and Terhardt (1974), carrying out carefully designed pitch matching experiments to rule out any possible artifacts, came to a conclusion that the pitch shift due to the intensity variation is not artifacts but facts. It should be noted, however, that even in these studies the extent of the pitch shift was smaller than Stevens showed. As mentioned above, there exists a large disagreement among the results on the pitch-intensity relationship. The purpose of this paper is therefore to present some evidences to elucidate this issue. For this purpose, several experiments were conducted under various conditions using *S*s experienced in psychoacoustical measurements and in musical performances. The second purpose of this paper is to examine whether a similar pitch shift for pure tones, if any, would be reproduced in the case of the relational pitch and also to discuss any possible mechanisms underlying these phenomena in relation to the theories of pitch perception. It is expected that the pitch-intensity dependence would offer some valuable implications for the mechanism of pitch perception, in the same manner as Van den Brink (1975) used the phenomenon of binaural diplacusis as a tool for learning about it.

Experiment 1

Method

Experiment 1 was designed to examine the pitch shift with the intensity variation and to establish the exact relationship between them.

Apparatus: A block-diagram of the apparatus used is shown in Fig. 1.

Procedure: The method-of-adjustment was used. Successive pure-tone pairs were presented to *S* repeatedly. One of the pair was a standard tone which was set at 125, 250, 500, 1000, 2000, 4000, or 6000 Hz, and its intensity level was varied in most cases from 20 to 80 dB above threshold in 10-dB steps by *E*. The other tone was a comparison tone, the frequency of which was adjusted by *S* and the intensity was set at 40 dB above threshold as the reference level. All tones were 600 msec in duration with rise-fall time of 25 msec and 600-msec intervals were inserted as the inter-tone interval in order to prevent any interactions between adjacent tones. These tone pairs were repeated periodically with inter-pair intervals of 1 sec. In half trials a comparison tone was proceded by a standard tone and on the other half the order was reversed so as to cancel the time-order error. *S* listened to these successive tone pairs through a headphone monaurally in a sound-proof room and matched the pitch of a comparison tone to that of a standard tone by adjusting the frequency knob of a variable oscillator to his satisfaction. The initial position of the frequency knob of the variable oscillator was varied randomly at the start of each run to be either above or below the point of frequency-match in a random way in order to avoid bias and knob--position cue. Eight adjustments were carried out at each intensity level for each frequency. The deviation of adjusted frequency of a comparison tone from a standard tone could be regarded as the measure of pitch shift due to the intensity difference between the two.

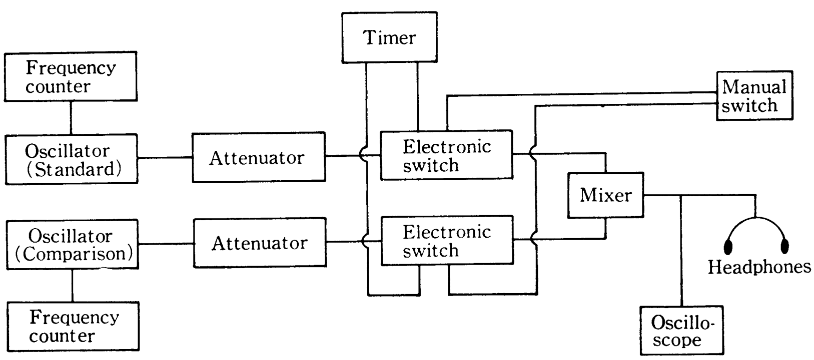

Fig. 1. Block-diagram of the apparatus

Subjects: There were three *S*s (K.M., T.S., and K.N.) with normal hearing ability and fairly fine frequency discriminability. They had both intensive training in psychoacoustical measurements and considerable musical experience as a member of an orchestra or a vocal ensemble, or of piano playing.

Supplementary experiment 1: In addition to main experiment described above, supplementary experiment 1 was carried out under two other modes of stimulus presentation using mainly subject K.M. One of them was *no-ISI* condition which contained no inter-stimulus interval between a standard and a comparison tone, and the other was the *manual-switch* condition in which *S* could switch on or off a desired tone at will by pressing a corresponding button with only one finger. In other respects details of the method were identical to those of the main experiment.

These modifications may make the pitch matching task easier and decrease the variability of adjustment. It is expected, therefore, any slight pitch shift due to the intensity variation could be detected more easily. On the other hand, there might be a possibility that any interactions between adjacent tones might occur because of temporal proximity. However, if identical results are obtained under three conditions of different temporal stimulus configurations, then it could be considered that no interactions should influence the results significantly.

Supplementary experiment 2: This experiment was designed using twelve other *S*s in order to examine whether the pitch-intensity dependence is observed by a larger population of *S*s. As the whole procedure employed in those experiments described above was very time-consuming, so the procedure was simplified in this experiment: frequency of a standard tone was 500, 2000, or 4000 Hz, and its intensity was 35, 55, or 75 dB SL, intensity of a comparison tone being fixed at 35 dB SL as a reference level. The inter-stimulus interval within a tone pair was 300 msec in this experiment. After a considerable amount of practice of pitch matching, four adjustments were carried out at each intensity level for each frequency. Other details of procedure were identical to those of the main experiment. *S*s were students of Tohoku University who had a normal hearing ability but had not special musical experiences.

Results and Discussion

It is assumed the frequency difference between a standard tone and a matched comparison tone is due to the intensity difference. Thus the measure of pitch shift caused by the intensity variation is given as follows:

$$\text{Pitch shift} = (\mathrm{F}_{comp} - \mathrm{F}_{std})/F_{std}\,.$$

Results of each *S* are shown in Fig. 2 (a-c), respectively. The relative pitch shift is represented as a function of the intensity level of a standard tone and parameters are frequencies of a standard tone. For subject K.M. data obtained from three different conditions (600-msec ISI, No-ISI, and Manual-Switch) were pooled as results of these conditions were quite similar to one another. Therefore, each data point represents the mean of twenty-four adjustments for this *S*, whereas of eight adjustments for T.S. and K.N.

It is noted from these figures that pitch of a pure-tone shifts slightly but systematically as a function of intensity. As presented in Fig. 2 (a) results of K.M. showed for middle and low frequencies except 125 Hz a systematic downward pitch shift as intensity increases and it appears that the more frequency lowers the greater the extent of pitch shift becomes. On the other hand, the non-monotonic functions were obtained for high frequencies, that is, as intensity increases pitch rises at first but then lowers. Furthermore, contrary to our expectations pitch of 125-Hz tone shifted upward with intensity, which is in an opposite direction of pitch shift to those of any other low frequency tones. Results of this *S* are regarded as most reliable because they are based upon more trials

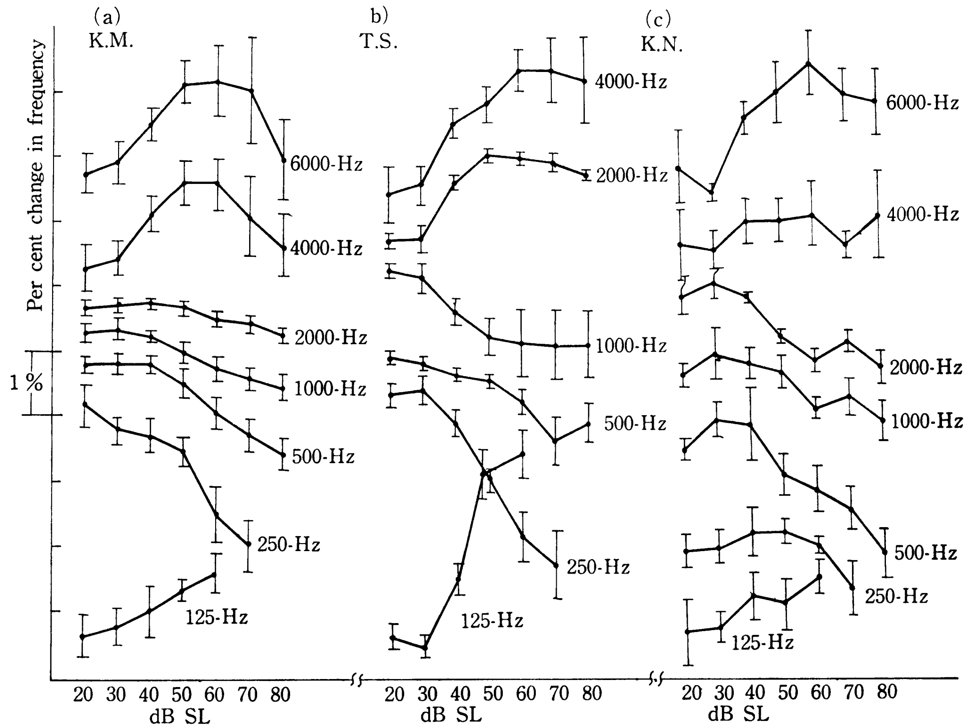

Fig. 2 a-c. Relative frequency shift needed to obtain a pitch match for two tones as a function of the sensation level of a standard tone. Each point represents the mean of twenty-four adjustments for subject K.M. or of eight adjustments for T.S. and K.N. Vertical bars show the standard deviation around the mean. Parameters are the frequency of a standard tone.

(8 trials × 3 conditions) and standard deviations are extremely smaller than other two *S*s. The standard deviations shown in the figure by vertical bars do not represent real variability of pitch matching of this *S*, because the results of this *S* are based upon pooled data from three experiments of different temporal conditions which were carried out at intervals of one or two months. If data of each conditions are represented separately, standard deviations decreases further compared with those shown in Fig. 2(a).

In principle similar results were obtained from the other two *S*s as indicated in Fig. 2 (b) and (c), although for these *S*s matching error were considerably large and curves obtained were not so systematic compared with K.M. It is noted that T.S. showed a large extent of pitch shift which amounts to 3% for 250 Hz and 125 Hz, corresponding to about 1/2 semi-tones in equal temperament scale. Although for K.N. the systematic pitch-intensity effect is not so clear as that of the other two, the general tendency of pitch shift is also observed in this *S* (Fig. 2(c)). The frequency region where pitch is independent of intensity seems to lie a little above 2000 Hz for K.M., between 1000 and 2000 Hz for T.S., and around 4000 Hz for K.N. The principal

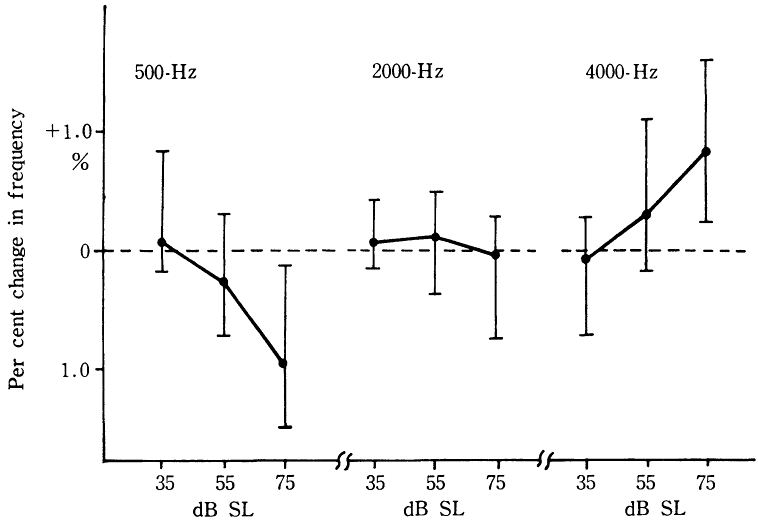

Fig. 3. Relative pitch shift as a function of the sensation level of a standard tone. Each point represents the median and vertical bars show the interquartiles for twelve subjects.

findings obtained in this experiment are summarized as follows: with increase in intensity, (1) downward pitch shift for middle- and low-frequency tones, (2) nonmonotonic pitch shift, that is, at first rising and then slightly falling, for high-frequency tones, and unexpectedly (3) upward pitch shift for the lowest frequency.

Results of additional experiment 2 with twelve *S*s are shown in Fig. 3. It can be seen from these figures that although the dispersion of the adjusted values is relatively large, the following tendencies are recognized: as intensity increases the pitch of a 500-Hz tone lowers, a 4000-Hz tone rises, but a 2000-Hz tone remains constant. The non-monotonic pitch shift observed in the main experiment was not reproduced here but the monotonic upward shift was for 4000 Hz. However, this can be regarded as not so crucial inconsistency, considering the facts that the present experiment was less sensitive to pitch shift because of relatively large individual differences and matching errors and that in the main experiment a clear non-monotonic shift was observed only for K.M. above 4000 Hz. Therefore, results of the supplementary experiment generally correspond with those of the main experiment, though the principal tendencies above described are not so conspicuous.

From all the results of the series of experiments described in this section it could be concluded that the intensity-dependent pitch shift indeed exists, not being artifacts but facts. It should be noted, however, that in contrast to the Stevens' subject who showed a considerably large pitch shift at low frequencies and higher extreme region, our *S*s showed a relatively small shift in response to corresponding intensity-level changes, in line with previous investigators (Terhardt, 1974; Walliser, 1969a; Gulick, 1970).

As pointed out in previous investigations, both relatively large matching errors and individual differences were found out also in present experiments. The matching error seems to have occurred largely as a result of *S*s' insufficient experiences in this type of pitch matching task. If these errors are large, then assumed pitch shift which was found here to be relatively small would be concealed, so *E* would fail to find it. The large individual differences mean that certain *S*s show typical pitch-intensity dependence but other *S*s do not, or even show the pitch shift in an opposite direction. This suggests the possibility that some psychological factors might have influence on matching performances, because it is difficult to account for such large variations in both extent and direction of pitch shift physiologically, as often suggested, by the location shift of the maximum excitation on the basilar membrane. If some other psychological attributes of tones such as brightness, volume, sharpeness, and so on, are less unequivocal and more variant among *S*s than pitch and if they have more or less influence on the pitch judgment, individual differences of pitch-intensity dependence would be accounted for by considering the influence of these attributes. It seems to be these intra- and inter-subject variability in effect of these attributes which may be called *timbre* on pitch that made the pitch-intensity dependence ambiguous in several previous investigations.

In this series of experiments relatively systematic pitch-intensity dependence was confirmed from three well-experienced *S*s and it was moreover reproduced by larger population of *S*s. It could be concluded, at this stage, that with increase in intensity high-frequency tones rise in pitch, low-frequency tones lower, but middle frequency tones remain constant.

Next, the problem of the distortion is needed to be considered because it is known that pitch of a complex tone deviates from that of a pure-tone of equal frequency. For example, Walliser (1969b) reported that pitch of a complex tone of 200 Hz is systematically lower than that of a pure-tone of equal frequency and Ohgushi (1976) also obtained similar results for complex tones below 1000 Hz. And distortion products generated as a result of nonlinearity of the apparatus used and the ear itself is known to increase with sound intensity. These imply the possibility that the pitch shift as intensity increases may be mediated by these distortion products rather than the effects of intensity itself upon pitch. However, this possibility seems unlikely since the distortion products at the highest intensity level in present experiments is not considered to be so large as to affect pitch. Nevertheless, it still remains possible that certain harmonic distortions may play a part in the pitch-intensity effect, as the distortion products generated within the ear are considerably large (Békésy, 1960), although those produced in the transducer are negligible (Pfeiffer, 1974).

Experiment 2

In the previous experiment, the pitch-intensity dependence was indeed observed for pitch matching of pure-tones. Then the question arises whether the pitch in musical contexts is also influenced by intensity changes. In order to answer this question we carried out following experiment in which judgements of the musical interval (relational pitch) were required when intensity variation was introduced.

Method

The details were largely the same with those of Experiment 1 with modification of allowing *S* to operate a switch which made the timing of stimulus presentation under his control, except that in this experiment he was instructed to adjust the certain musical interval instead of pitch matching so that pitch of a comparison tone got to the *dominant* in relation to pitch of a standard tone (the *tonic*) according to his internal criterion of the musical interval sense or relational pitch. When frequency of a standard tone was 125, 250, 500, or 1000 Hz, the upper *dominant* (the upward *perfect fifth* which corresponds to the frequency ratio of 2:3 in the natural scale) was adjusted, while when a standard tone was 2000, 4000, or 6000 Hz, the lower *dominant* (the downward *perfect fourth* which corresponds to the ratio of 4:3) was. The values of intensity level of a standard tone were identical to those of Experiment 1 and a comparison tone was also fixed in intensity level at 40 dB SL. The initial frequency of a comparison tone was varied randomly around the frequency of the *dominant* at the beginning of each trial. No time limits were imposed.

*S*s were K.M. and T.S. who participated also in Experiment 1 and showed the systematic pitch-intensity dependence.

Results and Discussion

The results of two *S*s are shown in Fig. 4 (a) and (b) separately, in which the relative deviations of adjusted frequency from physically determined frequency of the *dominant* are represented as a function of intensity changes. Parameters are frequencies of a standard tone (the *tonic*). If pitch of a standard tone is shifted with intensity as indicated in Experiment 1, it is assumed that the relational pitch (the *dominant* in relation to the *tonic*) should also be shifted in the same way. It can be seen, however, from Fig. 4 that K.M. showed almost no systematic shift of relational pitch with the intensity change for all frequencies. On the other hand T.S. showed a slight tendency of pitch shift, but its extent is negligibly small in comparison to his large pitch shift observed in Experiment 1. These results indicate that relational pitch is almost independent of intensity. This is quite contrary to the prediction from the results of Experiment 1. This discrepancy suggests that the pitch matching and the adjustment of relational pitch are different processes based upon the two different mechanisms of pitch perception. We will discuss this issue in a later section.

It is also noted that the dispersion of the adjusted values of relational pitch is as a rule larger than that of pitch matching data of the previous experiment, especially for high frequencies (4000 and 6000 Hz). This seems to be due to the fact that in this experiment the frequency of a comparison tone to be adjusted is different from that of a standard tone and so *S* had to rely upon only his internal musical interval sense in making adjustment. Our *S*s seem to have had considerably accurate and

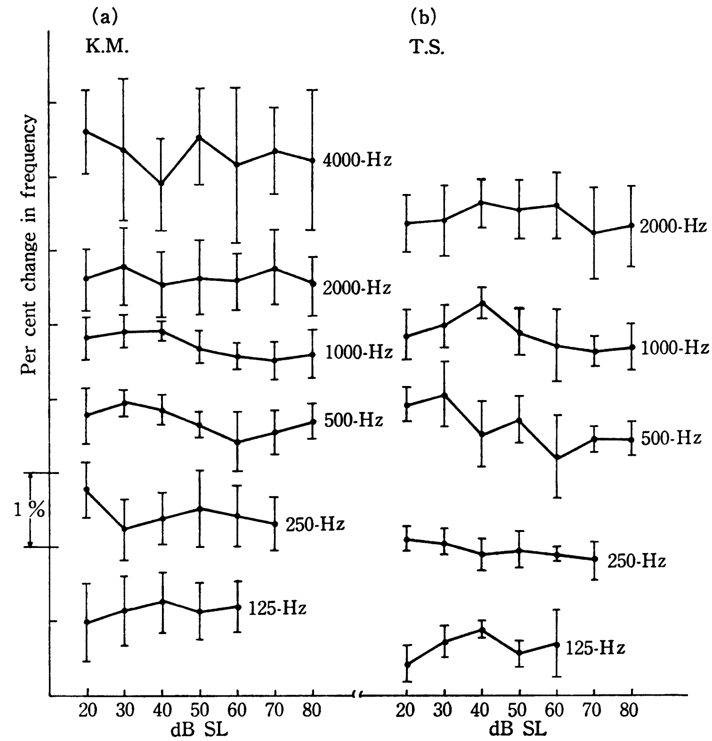

Fig. 4. Relative frequency differences between the adjusted and the physically determined as a function of the sensation level of a standard tone. Each point represents the mean of eight adjustments and vertical bars show the standard deviation around the mean. Parameters are frequency of a standard tone. The results for high frequencies are not shown here because of the large variability.

stable musical interval sense for middle- and low-frequency region but had much difficulty for high-frequency region. This is understandable through the previous finding that the tone chroma is lost at the frequency region beyond 4000 Hz (Bachem, 1948).

In relation to these results we refer to the study of Lewis and Cowan (1936) which is often quoted as the evidence that shows pitch of a complex tone is not influenced by intensity. They made *S* play a certain musical interval on the violin at different intensity and tried to examine the effect of intensity upon pitch by measuring the size of the musical interval. On the basis of results obtained through such procedure they concluded that pitch of a complex tone did not change with intensity. However, this conclusion cannot be drawn from their results because it is considered that the musical interval (relational pitch) is not influenced by intensity variation as our results revealed. In fact we have found that pitch of a saw-tooth wave tone changes uniquely with intensity performing the same pitch matching experiment. Some investigators also reported similar results. (Fletcher, 1934; Terhardt, 1975).

General Discussion

It is now needed to discuss the tonal property called *pitch* in detail and to define it. The word of *pitch* is generally used to mean the sensory dimension of tone height along the low-high continuum mainly dependent on frequency of tone. However, there has been a long controversy on this dimension among the German psychologists and the tendency to view it dualistically is deep-seated. For instance, Révész (1926, 1935, 1953), who proposed the *two-component theory* of pitch advancing the original dualistic theory of Brentano further, argued that there are two basic properties in the tone sensation: one is the *tone-height* which continuously changes with frequency, the other the *musical quality* which cycles when frequency is doubled. Likewise, Hornbostel (1926) differentiated *Helligkeit* and *Tonigkeit* in the same dualistic way, and Wellek (1935, 1963) also tried to grasp not only pitch but all other musical phenomena in a dualistic framework comprised of the *linear dimension* and the *cyclic dimension* corresponding to Révész's *two-component theory.* However, these analyses of pitch property did not necessarily succeed in giving a clear definition to the concept of pitch, only to introduce confusion into the terminology. Moreover, it is implausible that the two aspects of pitch property are phenomenally independent as Révész proposed. It seems, therefore, the dualistic theory of pitch is not acceptable in its original form and especially the *two-component theory* of pitch Révész postulated has much to be criticized (Aizawa, 1970). But we consider the significant implication of the dualistic theory for us is that the pitch is basically the musical characteristic proper to the tone sensation and it can appear differently according to the situations, rather than that pitch has two separate properties. This implication seems especially significant, because in recent experimental psychology pitch is seldom considered as the musical characteristic but usually as the general sensory dimension equivocally, coming to the result that the attention focused mainly to the psychophysical measurements of differential threshold or pitch-scaling such as mel-scale (Stevens et al., 1937) or Tohheit (Zwicker & Feldtkeller, 1967). This neglect of the musical characteristic of pitch might result in losing the substantial quality of pitch percept. Therefore, it may be more fruitful to grasp pitch from another point of view that is of the psychology of music, just as once von Helmholtz (1954) and Stumpf (1883, 1890) aimed at the scientific explanation of the musical phenomenon by studying the tone sensation.

Thereupon, we define the dimension of tone-height as the essentially musical characteristic, to which the term of pitch is given in a sense of the *musical pitch.* This means that the individual pitch is located within the relational structure of tones (the *tone-system*) and acquires the specific quality of its own in relation to the other tones. This quality could be called *tonality* or *tone-chroma* and the relational structure of tones could be called the *musical context.* This view of grasping pitch in the *musical content* means to deal with an individual tone in a tonal sequence or form, leading to the investigation of the perception of the musical phenomena such as the musical interval, harmony, or melody. (Attneave & Olson, 1970; Idson & Massaro, 1976).

In the experiments described above it was discovered that the pitch of a pure-tone changed with intensity in a pitch matching task but did not in a relational pitch task. It is supposed from these results that these two tasks dealt with pitch in two different situations of different degree of the *musical context.* Considering the details of these two tasks, in a pitch-matching task subject was required to match pitch of one tone to that of another, whereas subject was instructed to adjust a certain musical interval in a relational pitch task where he had to perceive pitch in the *musical context* according only to his internal musical interval sense rather than the impression of the sensory equivalence of pitch. Consequently it can be said that the relational pitch task dealt with the *musical pitch* and the pitch matching task with the *non-musical pitch* which could be called the *sensory pitch* for convenience' sake in a sense of weaker musical context†.

Considering in this manner the obtained results can be restated that the pitch as the musical characteristic (*musical pitch*) is not influenced by intensity but the non-musical pitch (*sensory pitch*) is more or less dependent upon it; the pitch-intensity dependence is nonmusical phenomenon. Pitch as the musical characteristic proper to the tone sensation is supported by the musical context but it loses its proper characteristic without the musical context and it appears rather as the sensory complex in which some dimensions such as brightness, volume, density, sharpeness and so on are mixed in an undifferentiated way. Supposing that *sensory pitch* is regarded as the undifferentiated sensory complex which may be called *timbre*, it is likely that *sensory pitch* (or *timbre*) continuously changes with intensity as well as frequency. For example, it may occur that the louder a tone is, the brighter or sharper it becomes for high frequencies and the more voluminous or the heavier it becomes for low frequencies. Possibly such changes of *timbre* with intensity can be cancelled by changing frequency. The influence of timbre upon the pitch comparison is supposed to be greater in the pitch matching task which dealt with *sensory pitch* in the relatively weaker musical context than in the relational pitch task which dealt with *musical pitch* in the full muscial content.

If the pitch-intensity dependence is the non-musical phenomenon and its extent is inversely related to the amount of the musical context, then the often observed individual differences in pitch shift could be explained from the fact that in a certain task each S perceives pitch in the different amount of the musical context according to his musical experience. In summary it is concluded that pitch as the musical characteristic does not change with intensity in the full musical context but is more or less influenced by intensity when it loses the musical characteristic in a weak musical context because the effect of *timbre* appears. In this sense Wever's statement

† The differentiation between *musical pitch* and *sensory pitch* is solely dependent on the degree of the *musical context.* It does not mean pitch can be separated into two independent properties.

that the pitch-intensity dependence is an illusion is not considered without good reason.

Next we shall turn to discuss the physiological evidences related to the pitch-intensity dependence, because this phenomenon is expected to offer some valuable implications for mechanisms of pitch perception. According to the place theory of pitch perception, pitch is determined by the place of maximum stimulation along the basilar membrane. This theory explains the pitch-intensity dependence is due to the shift of the place of the maximum because of the nonlinearity of mechanical property of the basilar membrane (Stevens & Davis, 1938). It may be that the stiffness of the basilar membrane increases with the amplitude of stimulation and this is possible to lead the shift of the place of the maximum. Békésy measured the phase difference between the stapes and a point on the basilar membrane 30 mm from the stapes when the amplitude of vibration was varied. He found that the phase difference between the stapes and the point of measurement steadily decreases with increasing amplitude. This means the wave length becomes larger and the pattern of vibration is displaced toward the helicotrema, corresponding to a lowering pitch shift. However, Békésy mentioned that the observed mechanical changes in the cochlear partition appears only with an amplitude of vibration above the threshold of feeling in normal hearing and therefore that most of the known changes of pitch with changes in intensity have the origin in neural rather than mechanical processes. Although there is not sufficient evidence to completely explain the pitch shift with intensity variation, it is still probable, however, that the nonlinearity of the mechanical property of the cochlear partition with increase in intensity produces the change in the pattern of stimulation on the basilar membrane.

On the other hand the periodicity theory of pitch perception predicts pitch is determined by the temporal spacing between the neural discharges. It seems difficult to explain the pitch-intensity dependence within this theory since it is implausible that the temporal spacing of neural discharges changes with intensity variation. Consequently the periodicity theory of pitch perception predicts that pitch does not change with intensity.

The existence of the pitch-intensity dependence poses a serious problem on the periodicity theory. However, it seems that this problem can be solved by differentiating *musical pitch* from *timbre*. As to the physiological correlates of *pitch* and *timbre*, Plomp (1967) mentioned that synchronism of nerve impulses should be considered as the only basis of pitch perception and the distribution of stimulation along the basilar membrane determines *timbre*. This establishes the physiological basis of our idea that pitch should be regarded as *musical pitch* in a situation with musical context but rather as *timbre* in a situation without musical context. According to these considerations our results that pitch as the musical characteristic (*musical pitch*) does not change with intensity, but *timbre* as an undifferentiated sensory complex does, can be explained physiologically from the fact that the periodicity of neural firing pattern does not change with intensity, but the distribution of stimulation along the basilar membrane does. It is considered that the pitch judgment in a pitch matching task was influenced by change of *timbre* on account of the impression that pitch is also changed as well as *timbre*, for it is difficult to separate *pitch* and *timbre* when both changed simultaneously (Jenkins, 1961). Consequently our conclusion is that it is not *pitch* but *timbre* that changes with intensity. This conclusion is consistent with the physiological mechanisms of pitch perception.

References

Aizawa, M. **1970** *Studies of the musical hearing.* (in Japanese), Tokyo: Ongaku-no-tomo.

Attneave, F. & Olson, R.K. **1971** Pitch as a medium: A new approach to psychophysical scaling. *Amer. J. Psychol.*, **84**, 147–165.

Bachem, A. **1948** Chroma fixation at the ends of the musical frequency scale. *J. Acoust. Soc. Amer.*, **20**, 704–705.

Von Békésy, G. **1960** *Experiments in hearing.* New York: McGraw-Hill.

Van den Brink, G. **1975** The relation between binaural diplacusis for pure tones and for complex sounds under normal conditions and with induced monaural pitch shift. *Acustica*, **32**, 159–165.

Cohen, A. **1961** Further investigation of the effects of intensity upon the pitch of pure tones. *J. Acoust. Soc. Amer.*, **33**, 1363–1376.

Fletcher, H. **1934** Loudness, pitch and the timbre of musical tones and their relation to the intensity, the frequency and the overtone structure. *J. Acoust. Soc. Amer.*, **6**, 59–69.

Gulick, W.L. **1971** *Hearing: Physiology and psychophysics.* New York: Oxford University Press.

Von Helmholtz, H.L.F. **1954** *On the sensations of tone: As a physiological basis for the theory of music.* New York: Dover.

Von Hornbostel, E.M. **1926** Psychologie der Gehörerscheinungen. *Handb. d. norm. u. pathol. Physiol.*, **11**, 701–730.

Idson, W.L. & Massaro, D.W. **1976** Cross-octave masking of single tones and musical sequences: The effects of structure on auditory recognition. *Percept. & Psychophys.*, **19**, 155–175.

Jenkins, R.A. **1961** Perception of pitch, timbre, and loudness. *J. Acoust. Soc. Amer.*, **33**, 1550–1557.

Lewis, D. & Cowan, M. **1936** The influence of intensity on the pitch of violin and 'cello tones. *J. Acoust. Soc. Amer.*, **8**, 20–22.

Morgan, C.T., Garner, W.R., & Galambos, R. **1951** Pitch and intensity. *J. Acoust. Soc. Amer.*, **23**, 658–663.

Nickerson, J.F. **1951** A study of some aspects of the intensity-pitch relationship. *J. Acoust. Soc. Amer.*, **23**, 148.

Ohgushi, K. **1976** On the role of temporal information in the pitch perception of complex tones. (in Japanese) *J. Acoust. Soc. Japan*, **32**, 710–719.

Pfeiffer, R.R. **1974** Consideration of the acoustic stimulus. *In W.D. Keidel & W.D. Neff (eds.) Handbook of sensory physiology*, Vol. 5/3, pp. 9–38. Berlin: Springer.

Plomp, R. **1967** Pitch, timbre and hearing theory. *International Audiology*, **7**, 322–344.

Révész, G. **1926** Zur Geschichte der Zweikomponentenlehre. *Zeitschr. f. Psychol.*, **99**, 325–356.

Révész, G. **1935** Tonsystem jenseits des musikalischen Gebietes. *Zeitschr. f. Psychol.*, **134**, 25–61.

Révész, G. **1953** *Introduction to the psychology of music.* London: Longmans.

Stevens, S.S. **1935** The relation of pitch to intensity. *J. Acoust. Soc. Amer.*, **6**, 150–154.

Stevens, S.S., Volkman, J., & Newman, E.B. **1937** A scale for the measurement of the psychological magnitude pitch. *J. Acoust. Soc. Amer.* **8**, 185–190.

Stevens, S.S., & Davis, H. **1938** *Hearing: Its psychology and physiology.* New York: Wiley.

Stumpf, C. **1883** *Tonpsychologie. I*; **1890** *II.* Leipzig: S. Hirzel.

Terhardt, E. **1974** Pitch of pure tones: Its relation to intensity. In E. Zwicker & E. Terhardt (eds.), *Facts and models in hearing*. Berlin: Springer.

Terhardt, E. **1975** Influence of intensity on the pitch of complex tones. *Acustica*, **33**, 344–348.

Verschuure, J. & van Meeteren, A.A. **1975** The effect of intensity on pitch. *Acustica*, **32**, 33–44.

Walliser, K. **1969a** Über die Abhängigkeiten der Tonhöhenempfindung von Sinustönen von Schallpegel, von überlagertem drosselndem Störchall und von der Darbietungsdauer. *Acustica*, **21**, 211–221.

Walliser, K. **1969b** Zusammenhänge zwischen dem Schallreiz und der Perioden-Tonhöhe. *Acustica*, **21**, 319–329.

Ward, W.D. **1970** Musical perception. In J.V. Tobias (ed.), *Foundations of modern auditory theory, Vol.* **1**. New York: Academic.

Wellek, A. **1935** Die Mehrseitigkeit der "Tonhöhe" als Schlüssel zur systematik der musikalischen Erscheinungen. *Zeitschr. f. Psychol.*, **134**, 302–348.

Wellek, A. **1963** *Musikpsychologie und Musikaesthetik*: *Grundriss der systematischen Musikwissenschaft*. Frankfurt/Main: Adademischer Verlag.

Wever, E.G. **1949** *Theory of hearing*. New York: Wiley.

Zwicker, E. & Feldkeller, R. **1967** *Das Ohr als Nachrichtempfänger. 2. erw. Ayfl.* Hirzel-Verlag, Stuttgart.

(Received October 30, 1977)