PSYCHOPHYSICS AND ITS APPLICATIONS
- LOUDNESS OF NON-STEADY STATE SOUNDS -

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Abstract

Basic research into psychoacoustics and its application is discussed. The psychophysical law should be robust in order to be applied to practical purposes. The importance to use appropriate psychophysical methods according to the purpose of the study and the necessity to develop new methods will be introduced. Various problems have to be considered when the findings in laboratory experiments are applied to real life situations. They are, for example, to control complicated variables keeping the reliability of the experiments for practical application, to cover wide area from static stimuli to dynamic stimuli and the necessity to take the effects of cognitive factors and ecological validity into consideration. A series of the process from basic research of psychoacoustics to its application was introduced using the loudness of non-steady state sounds as an example.

The basis of experimental psychology was initiated in Meiji era under the name of psychophysics in Japan. There existed experimental rooms for auditory and time perception as well as visual perception in the first laboratory of psychophysics in the University of Tokyo. The laboratory of auditory perception has long history. The details of the history of psychophysics in Japan are introduced in the literatures (Oyama 1998, 2001, Osaka 1998, Hinoda 1998, Nishikawa 2001, Sato and Sato 2005).

The definition of psychophysics and the approach to its application aiming a robust law that can be applied to real life situations

Stevens (1956) defined psychophysics in its broader aspects as the science of the response of organisms to stimulating configurations. Several psychophysical laws and methods for measurement have been proposed in various fields. As Gescheider (1985) noted that it can be expected that modern psychophysics contributes to solving practical problems by its laws and methods. However, it must be taken into account that psychophysical law usually has some limitations and that within the limit the law is valid. Several limitations in psychophysics should be considered.

(1) One of the limitations is related to ecological validity. It would be important that the law could be applied not only to the laboratory situation but also to real environment. In this sense, the application to practical problems may be a good opportunity to verify the law. When a psychophysical law is valid, we can estimate the sensation from physical measurement. This is very useful for applied purposes.

(2) Secondly, there are technical problems how to control the experimental conditions in order to find a psychophysical law in complicated real life situations. This is related to both methodology and ecological validity. Sometimes, it is necessary to develop new methods and new equipment in order to pursue this problem. It requires interdisciplinary knowledge of the phenomenon, insight or prospect about its background mechanism and skills for reducing non-essential variables.

If we try to investigate listening behavior in real world, then we may loose the level of precision in auditory experiments. We would like to discuss this conflict in the following section taking the loudness of non-steady sounds as an example.

Loudness of non-steady state sounds

Adoption of stimuli - From steady state sounds to non-steady state sounds

Steady state sounds are often used as stimuli in psychoacoustical experiments. On the other hand, several temporally varying phenomena such as speech and music cannot be examined with steady state sounds. The harmful effect using steady state sounds in psychoacoustical experiments are recently discussed in the books of Plomp (2002) and Neuhoff (2004).

Since 1960’s, we have been interested in auditory perception of non-steady state sounds. It was a worthwhile challenge to do this research. But it was not easy to control stimulus condition when we started to study using non-steady state. Since there was no equipment, it was necessary for us to develop the systems by ourselves to control and measure temporally varying sounds using techniques available in 1960’s (Namba et al., 1969, 1973). The episode will be introduced in my presentation

Psychological and physical model for predicting the loudness of non-steady state sounds - Representative value for the loudness of non-steady state sounds

In the case of the pitch of vibrate tone (tone with frequency modulation), the principal pitch is determined by the carrier frequency (Iwamiya et al., 1983). Listeners can detect rapid frequency change along temporal axis and also perceive the principal pitch as a representative value of vibrato tone.

Does the principal or overall loudness of non-steady state sounds exist? According to our daily life experience, we can easily judge the loudness of non-steady state sounds such as aircraft noise, car noise and human voice, etc. It is possible that the duration, the range and the speed of level (amplitude)-fluctuation of the sounds may influence integrating and/or averaging process of our hearing.

(1) At first, it should be discussed how loudness of non-steady state sounds is determined by the speed of fluctuation. In the case of sounds with rapid temporal change and short duration such as impulsive sounds, hearing may not pursue individual temporal fluctuation, but the loudness may be determined by an overall value of the stimulus variation. It should be investigated what kind of physical representative value is appropriate for such sounds.

(2) In the case of slowly changing sounds, it is possible to assign subjective evaluation to each portion of the fluctuation of the sounds. If Adaptation Level Theory proposed by Helson (1964) is correct, the loudness of non-steady state sounds will possibly correspond to the indifferent point of the responses, i.e. adaptation level. On the other hand, if Range-Frequency Model proposed by Parducci (1974) is adequate, the loudness will correlate to the midpoint between both ends of the stimulus range. If the power law proposed by Stevens (1972) is valid, the loudness may correspond to the average of sone values.

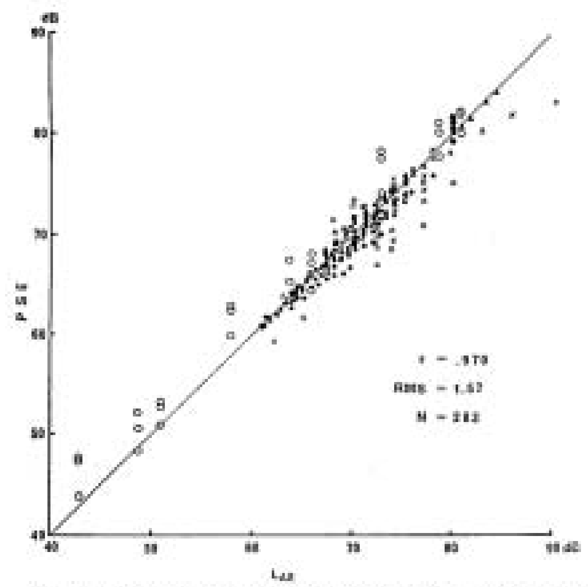
(3) In the case of sounds with longer duration and rapid or subtle change, each individual change may not be identified. It may be possible to assume that physical values during some period (e.g. psychological present) are converted to subjective values and they are averaged on psychological scale. The overall loudness may be determined by similar process in the case of slowly changing sounds.

Sensory averaging process is unclear, but it is hypothesized that short and rapid changes of sound may be physically averaged and the long-term loudness of level-fluctuating sounds may be averaged on psychological scale. When the period of sound is too long (e.g. several hours or days), some prominent portion during temporal stream may effectively contribute to the evaluation of overall loudness. .

Physical metrics of the loudness of non-steady state sounds
– Total and mean energy model -

Loudness of impulsive sounds.

In the case of sounds of short duration, the loudness increases as the duration becomes longer. This phenomenon shows that the ear integrates energy over time. If so, the total energy of sounds corresponds to loudness. There have been many studies of the additive effect of sound energy on loudness. The upper limit of the additive effect called the critical duration of loudness is less than 1 second and the value varies depending on the methods used in the measurement, experimental conditions, subjective clues, etc. (e.g. Scharf 1974).



The results of eight experiments on the loudness of impulsive sounds conducted by Namba *et al.* are plotted together. Good relation can be seen between L_{AE} and loudness expressed by PSE.

▲ Kuwano, Namba and Kato (1978)	impulsive sound with reverberation part
○ Namba, Kuwano and Kato (1974)	sound with rise time
□ Namba, Kuwano and Kato (1976)	sound with intensity increment (1)
● Namba and Kuwano (1981)	sound with intensity increment (2)
✦ Kuwano, Namba and Nakajima (1980)	impulsive sound with amplitude-modulated decaying part
▽ Nakajima, Kuwano and Namba (1979)	sound with rise time and sound with fall time
△ Nakajima, Kuwano and Namba (1980)	sound with intensity increment (3)
× Nakajima, Kuwano and Namba (1983)	sound with intensity increment (4)

$$L_{AE} = 10 \log \frac{1}{t_0} \int_{t_1}^{t_2} \frac{P_A^2(t)}{P_0^2} dt$$

where

$P_A(t)$ is the instantaneous A-weighted sound pressure; $t_2 - t_1$ is a stated time interval long enough to encompass all significant sound of a state event; P_0 is the reference sound pressure (20 μPa); t_0 is the reference duration (1 s).

Fig.1 Relation between loudness and L_{AE} of impulsive sounds (Kuwano et al., 1991)

Using brief sounds with various envelope patterns, the relation between loudness and the total energy of sounds was examined (Kuwano et al., 1991). Fig.1 shows the good correspondence between them. Sound exposure level (L_{AE}) is a physical index of total energy and defined in the caption of Fig.1. This suggests that L_{AE} is a good metric for the evaluation of sounds whose duration is shorter than the critical duration.

Loudness of non-steady state sounds with different durations.

The total energy of sound increases according to the increase of the duration. However, the total energy does not influence the loudness of sounds beyond the critical duration (Fig. 2-a). Loudness has a good correspondence with the mean energy level of non-steady state sounds with different durations (Fig.2-b). This means that the ear has averaging mechanism of energy longer than the critical duration and that this mechanism can average the level-fluctuation of sounds and contributes to giving a clue for overall loudness of fluctuation (Namba et al., 2006, 2007).

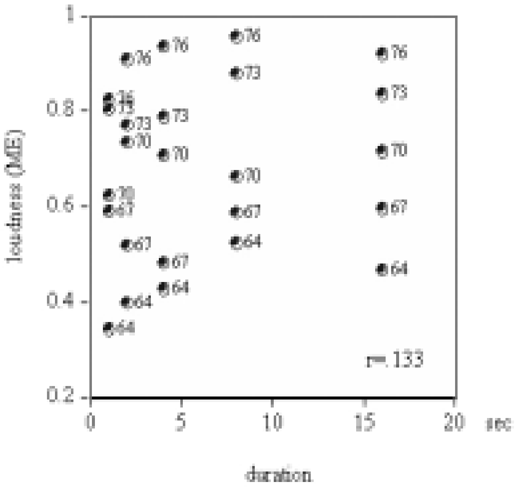


Fig.2-a Relation between Duration and Loudness
(Namba et al. 2006)

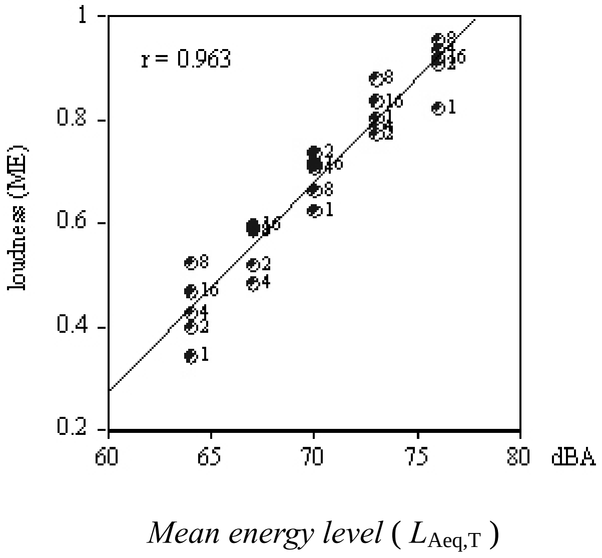


Fig.2-b Relation between loudness and mean energy level($L_{Aeq,T}$)
(Namba et al. 2006)

Loudness of sounds with various ranges and distributions.

According to AL theory and the range-frequency model, the ranges and distributions of sound level patterns may affect the loudness of level-fluctuating sounds. An experiment was conducted in order to examine the applicability of the theory and the model. White noise was used as stimulus and Programmable Sound Control System controlled the level patterns of noise. Point of subjective equality of loudness was obtained using the method of adjustment. The result showed that loudness did not correspond to the AL, the mean or median of dB scale, but showed good correlation with mean energy level as shown in Fig.3 (Namba et al 1972). The mean of sone values underestimated the overall loudness (Kato 1978).

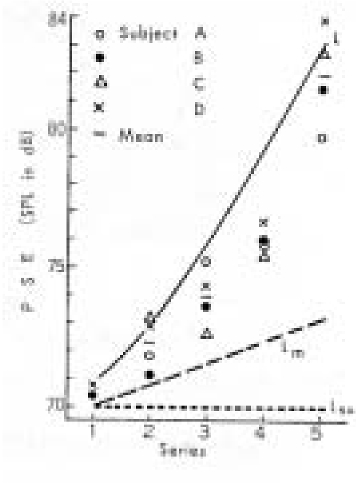


Fig.3 Relation between PSE(loudness), L(mean energy), Lm(mean dB) and L_{50} (median)
(Namba et al., 1972)

"Mean energy model" tells that the loudness of level-fluctuating sounds is determined by the mean energy level of the sounds regardless of the sound level patterns. This is a very simple model even from the viewpoint of psychophysics.

Application of the results obtained with artificial sounds to actual sounds

Is a simple law that the loudness of non-steady state sounds can be treated on the energy basis applied to the loudness of complicated sounds in real life?

In order to examine whether the mean energy model can be applied when various kinds of actual sound were judged in the different or the same stimulus context, a series of experiments was conducted. In the same context condition (Namba and Kuwano 1982), 9 kinds of sound were used. They were aircraft noise, Shinkansen train noise, ordinary train noise, road traffic noise, speech, music, impulsive noise, artificial level-fluctuating noise and steady state pink noise. The loudness of these sounds was judged using magnitude estimation.

PSEs of these sounds were calculated according to the procedure proposed by Marks (1974). He simply assumed that the same numeral of judgment means the same loudness.

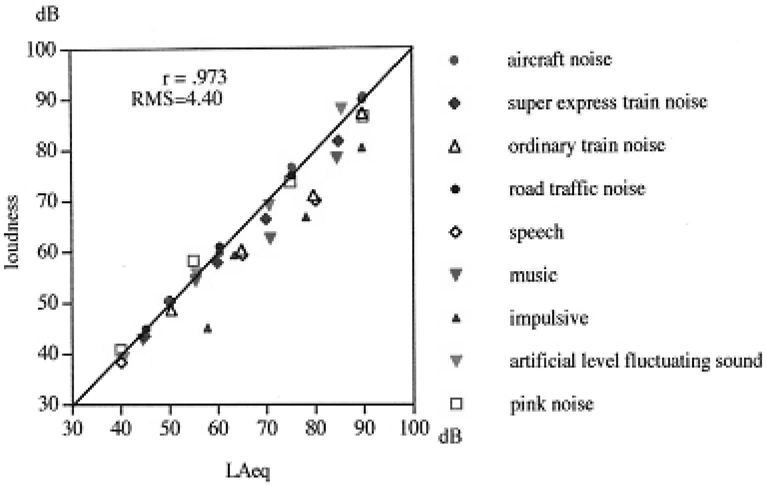
PSEs of all sound sources are shown in Fig.4. When the loudness of various sound sources was compared in the same context, a good correspondence between loudness and $L_{\mathrm{Aeq,T}}$ was found. In practical purposes, mean energy level corresponds to $L_{\mathrm{Aeq,T}}$ (A-weighted Equivalent Continuous Sound Pressure Level) which is standardized as ISO 1996 and defined in the caption of Fig.4. In a series of experiments under different stimulus context (Namba et al. 1978), the mean energy level showed a good correlation with loudness (r=0.979, N=230). These results indicate that mean energy model can be applied to the loudness of various non-steady state sounds existing in real life environment.

Comparison among magnitude estimation, rating scale and method of adjustment

PSEs were calculated from magnitude estimation on the basis of the assumption of Marks (1974). This conversion is valid if there is no context effect (Marks 1988; Fagot & Pokorny 1988). To avoid context effects, it is appropriate to obtain *PSEs* from the method of adjustment, which is thought to be hardly affected by context (Hellman 1976). Additional experiment was conducted using the same sounds and the loudness of the sounds was matched with that of steady state sounds using the method of adjustment.

High correlation was found between loudness and $L_{\mathrm{Aeq,T}}$ (r=.971). *PSEs* calculated from magnitude estimation were found to be similar to *PSEs* obtained by the method of adjustment.

The assumption of Marks is verified and it is very efficient. It took longer time in the experiment using the method of adjustment than in the experiment with magnitude estimation more than by the factor of 10.



$$L_{\mathrm{Aeq},T} = 10 \lg \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^{\,2}(t)}{p_0^{\,2}} \, dt \right]$$

where

$L_{\mathrm{Aeq},T}$ is the equivalent continuous A-weighted sound pressure level, in decibels, determined over a time interval T starting at t_1 and ending at t_2;

Fig.4 Relation between loudness and $L_{\mathrm{Aeq,\,T}}$ of various kinds of non-steady state sounds (Namba and Kuwano 1982).

Another additional experiment was conducted using category scale with the same sounds. High correlation was found between category scale and $L_{\mathrm{Aeq,T}}$ (r=.981, N=77). This experiment was conducted in a group in a lecture hall. All participants were divided into two groups and the other group judged the sounds using magnitude estimation. High correlation was found between magnitude estimation and $L_{\mathrm{Aeq,T}}$ (r=.969, N=90). The validity of $L_{\mathrm{Aeq,T}}$ as a metric of non-steady state sounds was confirmed in a general environment such as a lecture hall.

It was found by the experiments using different methods and conducted in different rooms that $L_{\mathrm{Aeq,T}}$ is a good metric of loudness of level-fluctuating sounds. $L_{\mathrm{Aeq,T}}$ is a robust metric regardless of sound sources and methods for the measurement of loudness.

Applicability of ratio scale and interval scale

It is an important and basic topic in psychophysics whether power law or logarithmic law is valid between physical values and sensation. In a series of experiments above mentioned, magnitude estimation produced power law and a logarithmic law was obtained when a category scale was used. The relation between magnitude estimation and category scales is not linear; a linear relation between them can be expressed by converting the magnitude estimations into logarithmic values. This calculation produced a correlation of 0.98. The results suggested that the both methods measured the parallel tendency for the same stimulus series.

Torgerson (1960) has shown that, when subjective impressions are converted into judgments, the two types of scaling procedures generate different results. Therefore, it is possible that whenever magnitude estimation or category judgment is employed, the experimental results are determined by the participants' adaptation to the experimental situation. This problem was discussing in the other papers in detail (Namba 1969, Namba and Kuwano 1991).

To avoid the ambiguity of a sensory scale (whether it is an equal ratio or equal interval scale), it is preferable to use *PSE* in practical situation. This is because *PSE* is sufficient as a representative value of fluctuating sounds when environmental sounds are measured using a sound level meter. The information is needed that equal value of the indicator of a sound level meter shows equal loudness within some range of error.

In practical situations, the sone scale has an advantage that it can be added since it is a ratio scale. When there are several sound sources that have complicated frequency components in the environment, loudness level is calculated according to the method standardized in ISO 532B as follows. The sound pressure levels of each critical band are converted into corresponding sone values and overall loudness is calculated as a summation of sone values of each critical band taking the masking into account. This is an example of loudness summation in frequency region.

On the other hand, category scale obtained by the method of successive categories, for example, is an interval scale and there is no additivity of the scale. However, mean values can be calculated and used for the estimation of permissible level of environmental noise and the evaluation of comfortable sound situation. The category subdivision method proposed by Heller et al. (1985) was standardized as ISO 16832 (Acoustics- Loudness scaling by means of categories) in 2006 for loudness measurement in the field of audiology as in the case of hearing aid fitting.

It would be productive to use appropriate methods and scales according to the purpose in the application. There is no psychological method free from biases. Psychophysical methods are tools and appropriate methods should be used for the purpose of measurements.

$L_{\mathrm{Aeq,T}}$ and Environmental Quality Standard

What metric is appropriate for the evaluation of the loudness of level-fluctuating sounds is closely related to the applied problems such as the evaluation of road traffic noise and machinery noise. It is also related to legal matters such as Environmental Quality Standard and has a social effect. Median (L_{50}) was used as a metric of level-fluctuating sounds such as road traffic noise in the Environmental Quality Standard in Japan. Metrics based on maximum level (L_{Asmax}) has been used for Shinkansen train noise and aircraft noise. The Environmental Quality Standard for general environmental noise including road traffic noise was revised adopting $L_{\mathrm{Aeq,T}}$ as a metric in 1998 on the basis of the report of Central Environmental Council. We were involved in this revision. JIS Z8731 “Acoustics – Description and measurement of environmental noise” was revised in 1999. Our papers are referred in JIS Z8731 as an evidence showing good correlation between $L_{\mathrm{Aeq,T}}$ and loudness.

After the revision of the Environmental Quality Standard for general environmental noise, the Environmental Quality Standard for aircraft noise is now being revised adopting $L_{\mathrm{Aeq,T}}$ as a basic metric and we are engaged in this revision.

This fact shows that our basic studies contribute to the administration of the environment. Our contribution is not only through our research in the laboratory, but also through activities in the committee in central and local governments. This is an example that basic studies of psychophysics have contributed to the applied issue.

Other topics to be considered in application of psychophysics

A conclusion has been obtained that equal value of $L_{\mathrm{Aeq,T}}$ indicates equal loudness of various kinds of sounds. However, when $L_{\mathrm{Aeq,T}}$ is used as a metric of loudness, there are various problems. They are, for example, time interval of the application of $L_{\mathrm{Aeq,T}}$, and cognitive effect in the case of the evaluation of actual sounds that inevitably occurs when the sound sources are identified. These problems will be discussed in the following sections.

Time interval of the application of $L_{Aeq,T}$ - Instantaneous impression and overall loudness-

In the evaluation of the environment, the reference time interval may be one day, one week, one month or one year. It is not realistic , for example, that the ear can integrate the total energy of sound for one year and then averages the energy to correspond to the overall loudness. It is assumed that listening to the sound along temporal stream, we may grasp the information of the sound within each time window (i.e. psychological present) and perceive the loudness of the sound averaging the energy within the time window. Since conventional

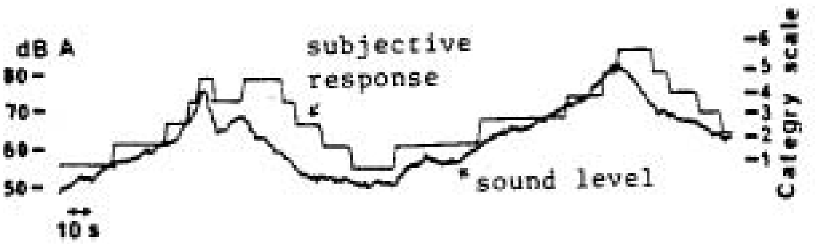


Fig.5 An example of the record of the method of continuous judgment by category. (Kuwano and Namba 1985)

psychophysical methods such as method of constant etc. cannot measure subjective impression along sound stream, we have developed a method, called “the method of continuous judgment by category” (Kuwano and Namba 1985). An example of the result of this method is shown in Fig.5. The details of this method and its results will be discussed in my presentation.

To measure the overall loudness based on long-term experience, memory research is needed. When dose-response relationship is examined in social surveys, good correlation is found between $L_{\mathrm{Aeq,T}}$ and the responses of residents. An example of the results recently obtained by a social survey through internet is shown in Fig.6 (Kaku et al. 2007). Good correlation can be seen though it is not clear whether the responses indicate loudness or complicated annoyance.

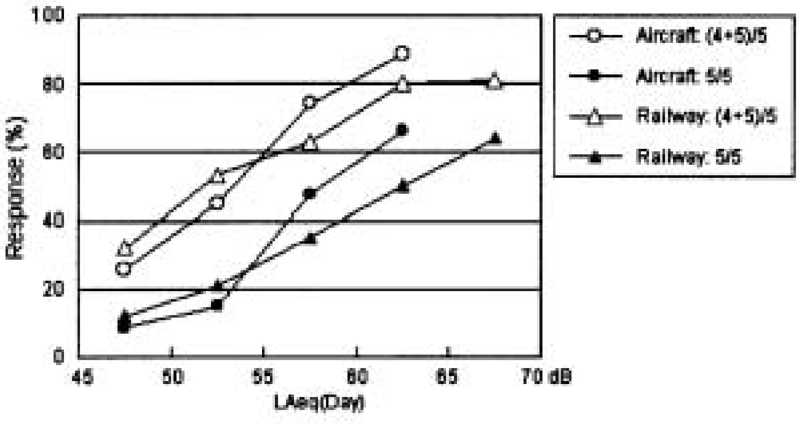


Fig.6 Dose-response relation between L_{Aeq}(Day) and respondents’ annoyance by internet survey. (Aircraft: N=588, Railway: N=448) (Kaku et al., 2007)

Cognitive factors

$L_{\mathrm{Aeq,T}}$ is used as a basic metric in the standard for environmental noise in many countries. However, since there may be a difference in loudness among sound sources even if the values of $L_{\mathrm{Aeq,T}}$ is equal, sometimes correction is used. For example, in some European countries 5-dB is added to the permissible level for train noise (so called “rail bonus”)(Fastl et al 1996). On the other hand, some studies reported that no rail bonus was found in their results in Japan (Kaku 1996). Since there is a cognitive effect on the evaluation of sounds in real life situations, $L_{\mathrm{Aeq,T}}$ is used as a basic metric and different values are used or some correction is added for determining the permissible levels according to the sound sources. Cognitive effect is considerable especially in the judgments based on memory and experimental research is being conducted in order to examine the relation between $L_{\mathrm{Aeq,T}}$ and recalled loudness including the effect of cognitive factors (Kuwano et al.1988, 2003).

Summary

The information of the relation between physical values of sounds and subjective impression is required not only in the laboratories of psychology but also in many practical situations such as the evaluation and design of the sound environment and design of machinery sounds. In the field of psychoacoustics a law is being sought in the perception of sound varying temporally in a complex manner. This is because that information of various sounds in our environment such as speech, music and machinery sounds is conveyed by the temporal variation along the temporal stream and it is a role of hearing to receive the information. Steady state sounds are often used in the traditional studies of psychoacoustics. Steady state sounds have an advantage that it can be easily controlled. However, characteristics of hearing that obtain information from the temporally varying stream cannot be examined by the experiments using steady state sounds. On the other hand, many aspects in hearing can be examined by experiments using non-steady state sounds.

A series of the process from basic research of psychoacoustics to its application was introduced using the loudness of non-steady state sounds as an example. It included generation and control of complicated stimuli, examination of psychological and physical representative values of temporal variation, proposal of the mean energy model as a metric of loudness of level-fluctuating sounds and adoption of $L_{\mathrm{Aeq,T}}$, i.e. A-weighted equivalent continuous sound pressure level, to the Environmental Quality Standard of Noise in Japan. In addition, problems were introduced and discussed when $L_{\mathrm{Aeq,T}}$ is applied to the loudness of various kinds of non-steady state sound. They were, for example, reference time interval, the effect of envelope patterns, problems related ratio scale and interval scale, cognitive effect and the use of methods as a tool.

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