Transient responses of human sensory systems

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An indoor climate has heterogeneous environmental factors, usually we work on noise, thermal sensation, light conditions etc. and they fluctuate. Discussions on the behaviors of our sensory systems for the fluctuations are very important as well as steady change. For that, it is important to grasp their linear responses to precede further non-linear behaviors. The transient response of each sensation in the form of an impulse response was measured on its specific subjective scale; loudness for noise, hot and cold for thermal sensation and brightness for visual sensation. It is shown how each was measured. After each impulse response was obtained, all were gathered to be compared with. Each impulse response has an abrupt rise and the later response is different with each other. The hearing system has a large negative reaction, and thermal sensation has a shaking reaction in negative and positive. On the other hand, visual system for brightness has a smooth decrease on the positive side.

Keywords; Linear transient response, hearing system, thermal sensation, visual system

Introduction

An indoor climate has heterogeneous environmental factors, we usually work on noise, thermal sensation and light conditions and usually they fluctuate. Discussions on the behavior of our sensory system for fluctuation are very important as well as steady change. For that, it is important to grasp each linear response. The method to measure the linear behavior of each system in the form of an impulse response is discussed. It is true that each sensory system has a non-linear response to an input stimulus, but we must not miss the linear response lying in the fundamental to precede further non-linear behaviors.

First, it is important to find how a linear response happens on each subjective scale. In order to find an impulse response we have to discuss how we can make a Delta function as an input to each system, it is practically in a rectangular form. Then, the response of the system is measured to get an impulse response.

It is interesting to see how the linear response corresponds to a fluctuating input, if it is calculated with the impulse response. An impulse response for loudness was already measured [1]. It was found that a sound is absolutized before the binaural hearing process [2]. There, for an impact sound, it was convolved with the impulse response of hearing system and the result was absolutized. It was integrated for the time window of 40ms and the loudness of the sound was well estimated [3].

For thermal responses, the increasing and decreasing temperature change from the neutral temperature were given and the responses were separately treated. For each side a step function was given and the response was obtained for skin temperature, thermal sensation and un-comfortableness. After this, the response was time-differentiated to have its impulse response.

For brightness or luminance response, its positive or negative signs were defined when it was brighter or darker than the back ground luminance of adaptation, respectively. The time interval of two light pulses of the same luminance was changed and the luminance of the pair was compared with 5 single light pulses and the most similar one was pointed. Just the same way as the impulse response of hearing system was measured.

In this paper, each sensory response was measured in the form of an impulse response and all were gathered and compared.

1. Hearing system [1] [2] [3]

(1-1). Outline of Experiments

The impulse response was measured for a rectangular pulse of 0.05ms duration which was created by the convolution with the inverse filter of the loud-speaker to correct its distortion. The time interval between two positive pulses of the same amplitude or a positive and a negative pulse was varied, and the loudness of a pulse pair was compared with a preceding single rectangular pulse having the same duration of 0.05ms and a subject was asked to find the most similar loudness among five pulses which had 0.2 amplitude differences.

Fig.1 shows the averaged variation of loudness with the change of time interval, when the signs of two pulses with the amplitude of 93dB were one positive and one negative shown in (i), and both positive in (ii). The ordinate shows a comparison pulse amplitude whose loudness is the most similar to that of the pulse pair and is called loudness magnitude in figures of this paper to distinguish from "loudness" (in sone) which has been historically used. The same measurement was done for the amplitude of 86 dB.

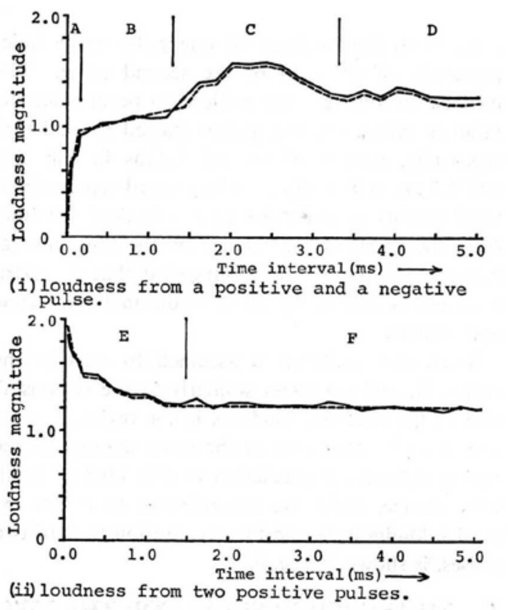


Fig. 1. Loudness change of a pulse pair depending on a time interval

(i) the pair had a positive and negative pulses and (ii) it had two positive pulses. A solid line shows the result from a rectangular pulse of 93dB and a dotted line that of 86dB.

In addition to the interference response, the loudness increase which does not depend on the signs of pulse pair was observed to occur after the point at which the two pulses started to be heard as separated. Subjects, in average, started to hear them as separated stimuli at around a time delay of 1.4ms when two positive pulses were presented. When a positive pulse followed by a negative pulse, they did so at around 1.7ms. They heard two pulses clearly separated at around 4.0ms still with a small loudness increase compared with one pulse alone. When heard separately, a tonal quality to the pulse pair is noticed resulting from the spectrum determined by the time interval between the pulses. It is suggested that the extra loudness is caused by these additional pure tone components. After subtracting the loudness increase from the total loudness of a pulse pair, the transient response curve in the interference region was obtained and is shown in Fig. 2. The thick line shows the average response of the twelve subjects.

(1-2). Discussions

The frequency characteristic in Fig.2 is completely different from the equal loudness curve generated by pure tone comparisons (see I.S.O.). The reason is that low pitch sounds are excited by the rectangular pulse which has wide frequency content.

It is very interesting that in the range 50 to 80 ms, eight of the twelve students perceive the pulse pair as being composed of three or more linked pulses. The time interval between two pulses gives the main spectral component at

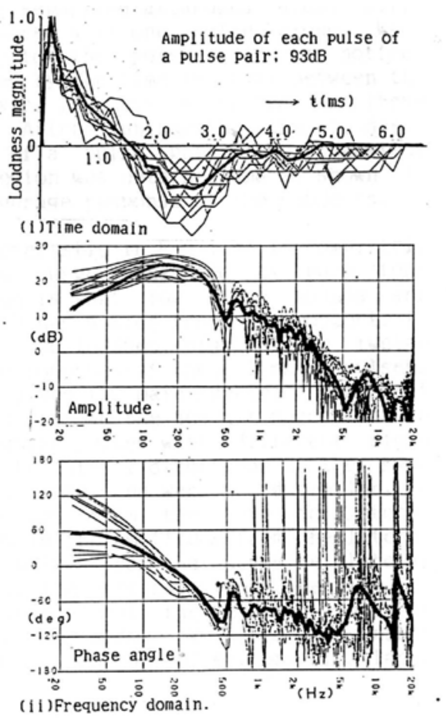


Fig. 2. Impulse response of hearing system obtained from the measurements of 12 male students;

(i) Time domain and

(ii) Frequency domain

12 to 20Hz. This response maybe related to the Gestalt perception in the hearing system.

When two rectangular pulses with different signs were heard binaurally from the opposite lateral directions at the same time, they were added in the absolute forms and were heard similar to the loudness of two positive pulses from the opposite lateral directions or the single pulse of double the amplitude from one lateral direction [2]. The localization of two pulses from the opposite lateral directions was a little different in the vertical plane depending on their signs.

Now for an impact sound, it was convolved with the impulse response of hearing system and the result was absolutized. It was integrated for the time window of 40ms and the loudness of the sound was well estimated [3].

For the reflection of a large plane panel and that of a small one, the temporal integration of the absolutized instantaneous loudness of each sound field was calculated. The former got 2.3 dB and the latter 0.7 dB larger than the direct sound. It was asked to 4 students which sound field was larger. All of them distinguished the former reflection was larger [2].

2. Thermal sensation system [4]

When air temperature or thermal radiation in a room varies, our skin temperature and subjective vote change very complicatedly in the non-linear aspect of the thermo-regulatory system. However, in the macroscopic point of view, responses based on the linear relationship are also observed. We can have an abrupt and rapid change of air temperature or thermal radiation, and obtain thermal sensation and subjective votes following the change [4].

When an output response for thermal sensation or un-comfortableness to the step function input of air temperature or thermal radiation is differentiated by time, the impulse response for each of them is obtained. The impulse response on each subjective vote is convolved to a varying air temperature on the linear simulation in order to compare with each experimental response to the change.

(2-1). Outline of experiment methods

An artificial climatic chamber was temporarily constructed in the anechoic chamber of Kansai Univ. whose walls were covered with 20cm thick glass fiber layers. Their surfaces were covered with sheets of wall paper. Plywood panels with a vinyl sheet cover were arranged on the floor. Forty minutes were given prior to the experiments for getting used to the neutral temperature. Votes for thermal sensation, un-comfortableness and good to bad estimation were recorded every minute on each interval scale as well as skin temperature change. Each sensation scale has been used for steady state, but here it was used also for the transient response with the interval scale. Neutral temperatures in winter and summer were set to 21°C and 25°C, respectively. High temperatures for the step function input were set to 28°C in winter and 31°C in summer and low temperatures to 15°C in winter and 19°C in summer.

(2-2). Impulse response of local skin temperature

Fig. 3 shows a few of the impulse responses of local skin temperature. It has the highest first peak with a following complicated response. It seems to differ from one another and the response at the forehead has the largest first peak which appears first among the other peaks. The later deviation after the first peak must have a very complicated response related to the psycho-physiological mechanism of the system. In spite of the same physical conditions, the deviation after the first peak on different days is not reproducible and looks to change at random. However, the latency time of the first peak at each local skin temperature does not differ much and does not show much individual difference.

(2-3). Impulse response of each subjective vote

Figs. 4 show an example of impulse responses on the vote of thermal sensation of three male students measured in winter. Fig. 4 (a) is at the raise of air temperature and Fig. 4 (b) is at the decrease of it. Each subject has a

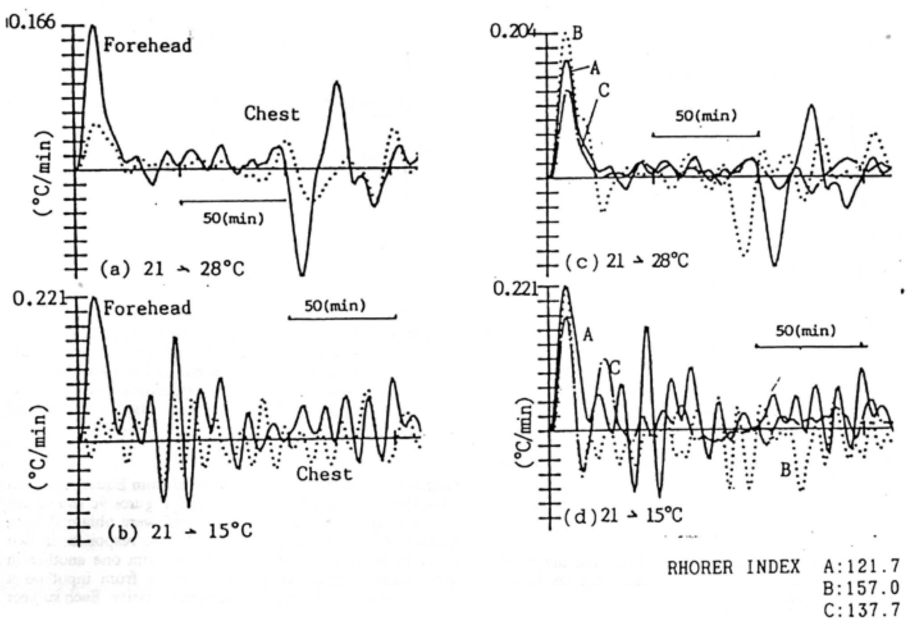
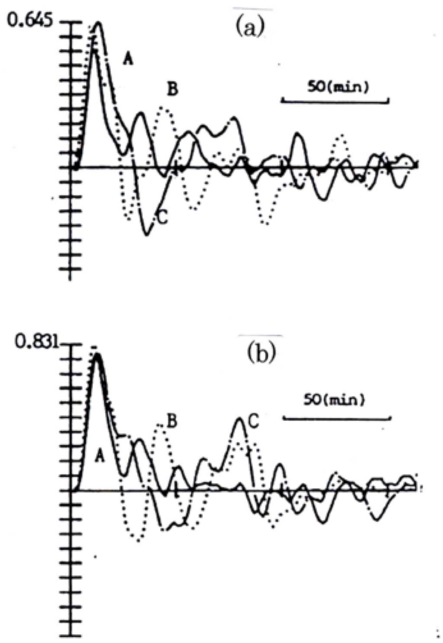


Fig. 3. Temperature change at the forehead and chest in (a) and (b) and the forehead temperature difference among three students in (c) and (d)



Figs.4. Impulse response of thermal sensation of three different students

(a) shows when temperature was raised from 21 to 29°C and

(b) shows when it was decreased from 21 to 15°C

relatively different response. On the other hand, the first peak is predominantly observed, and its latency time is just slightly different from each other. The response at the decrease of air temperature deviates more frequently than that at the increase as in the case of skin temperature. Though the first peak has a relatively stable reproduction, the successive response depends on the subject and changes at each time of experiment, and the change looks to appear at random.

Fig. 5 shows impulse responses on thermal sensation averaged by nine subjects on different days. It is observed that the first peak of the subjective vote becomes clearer and more predominant by averaging, and the successive response becomes smoother.

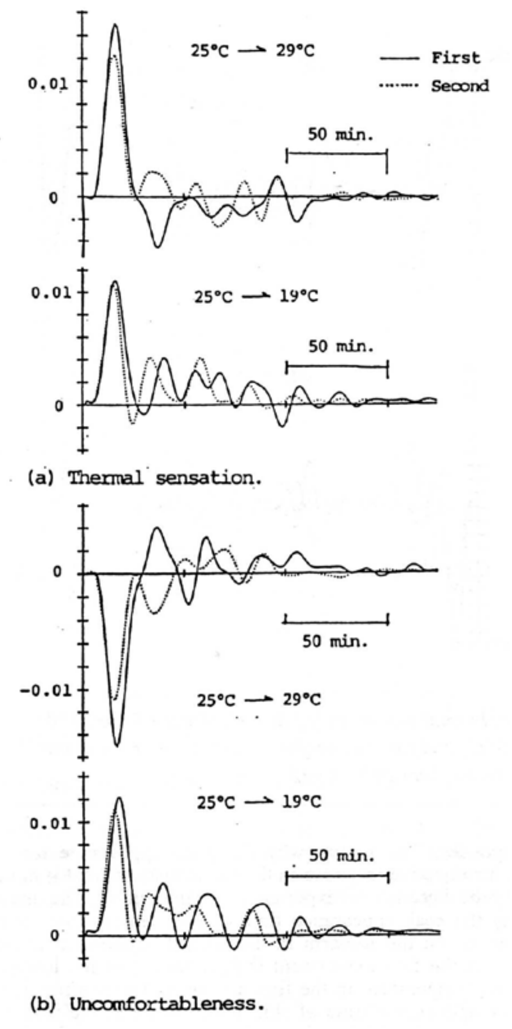


Fig. 5. Impulse response of (a) thermal sensation and (b) un-comfortableness to raised and decreased air temperature, averaged by nine students, on different days.

Impulse responses were measured only at the raise of thermal radiation. Fig. 6 shows the averaged impulse responses of four students for the case.

The maximum cross correlation coefficients between impulse responses of local skin temperature and a subjective vote were calculated and very large, but the interesting point is that it is difficult to point which local skin temperature always informs the subjective vote.

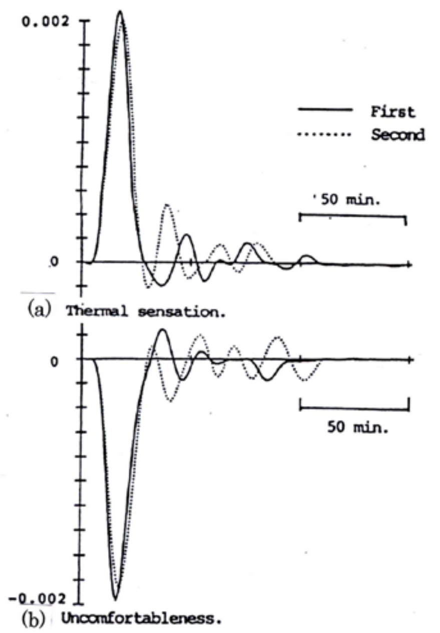


Fig. 6. Impulse response of (a) thermal sensation and (b) un-comfortableness to raised thermal radiation averaged by four students, on different days.

(2-4) Estimation to arbitrary varying temperatures with the linear simulation

When varying air temperature is given with the solid line of the highest row of

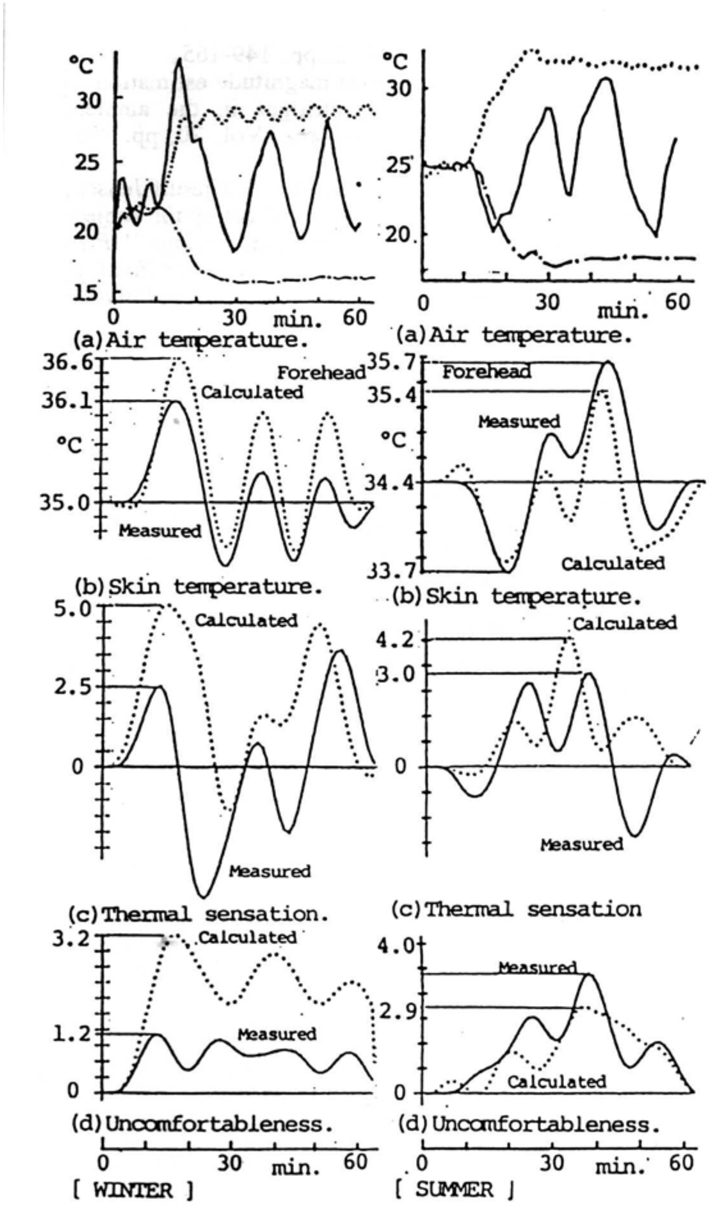


Fig.7. Measured and calculated responses of (b) skin temperature, (c) thermal sensation and (d) un-comfortableness to the varying air temperature in (a) by the linear simulation.

Fig. 7 in summer or winter, responses of skin temperature, thermal sensation and un-comfortableness are compared below, being calculated by the linear simulation. calculated results are shown by dotted lines and measured ones by solid lines. Since the range of the variation of air temperature was above the high temperature of the step function for an impulse response measurements in winter, which are shown by dotted and chained lines, correspondence of the measured and the calculated results is worse than that in summer.

When an impulse response was measured, each response was given with the interval scale. It means that the response was given on the magnitude estimation. The thermal sensation scale does not look to be linear. It is very difficult to find the function for the estimation scale for thermal sensation and un-comfortableness.

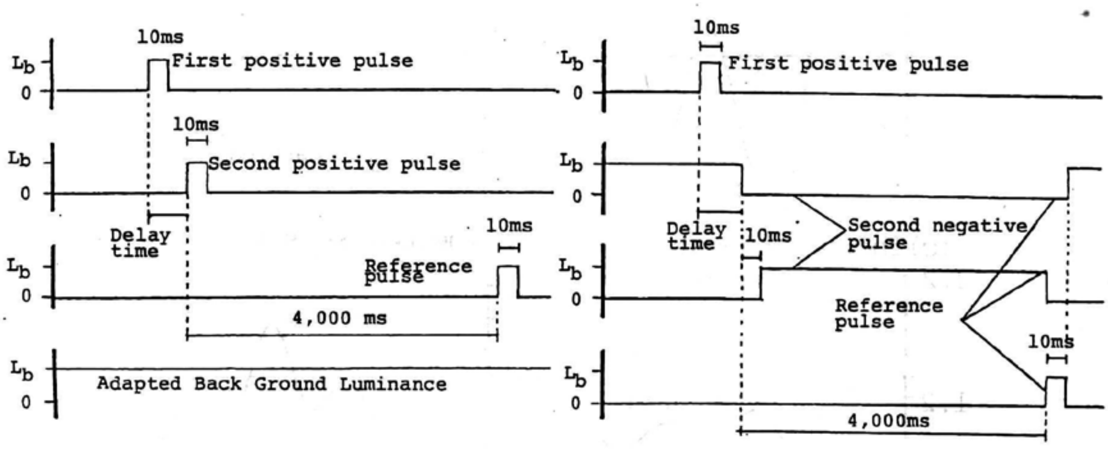
3. Visual system

The linear behavior on brightness or luminance for two positive light pulses, or a positive and a negative one is also investigated to find an impulse response. The physical amount for a light pulse is called its magnitude, and the subjective response to it is called its luminance. The time interval of a pair of light pulses, whose magnitudes are the same through an experiment, was changed. It was defined “positive” when it is brighter than the adapted background luminance and “negative” when it is darker. Its luminance was compared with five single light pulses to prefer the most similar one, as in the loudness experiment for a rectangular sound pulse.

(3-1). Outline of experiments

A light pulse was presented at the center of the screen which has a fixed uniform luminance. The pulse width was 10ms, i.e., the luminance change over 100Hz was not treated. To obtain the light pulse, a magnetic shutter was inserted in the light path, and its pulse width and time interval were controlled by the shutter time. The on-off switch for the shutter was operated by the electrical signal from a personal computer. The dimension of the screen was 770mm ×460mm. The diameter of the aperture for a light pulse stimulus was 42mm whose visual angle was 7 degrees.

To give a pair of two positive light pulse stimuli, four light sources with three shutters were used as shown in Fig. 8 (i). The fourth light source was adjusted to the background luminance in order to have the same luminance in the aperture. To get a positive and a negative one, four light sources and shutters were used as in Fig. 8 (ii). A single pulse for comparison in the negative sign was obtained by three shutters with the combination of a negative and a positive pulse whose absolute magnitude was below the background luminance. The largest magnitude of a negative light pulse was decided by the adapted background luminance and accordingly, the one for a



(a) Two positive light pulses (b) A positive and a negative light pulse

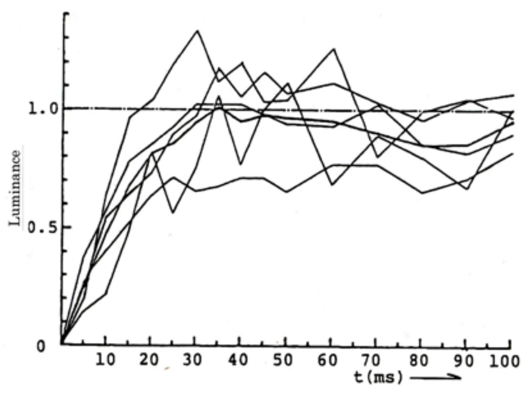
Fig. 8. Pulse pair and a reference pulse with the combination of shutters

positive pulse was decided.

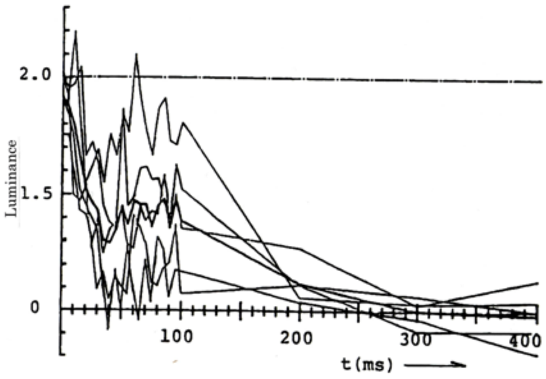
In this experiment, the adapted background luminance was 10cd/m^2 and the magnitude of one of the light pulse pair was chosen 10cd/m^2 when it was measured by the luminance meter keeping its shutter open. The magnitude was controlled by the combination of the dimmer and/or light filters. The time interval between a light pulse pair and a comparison single light pulse was four seconds which was found to be long enough not affecting each other and to be able to memorize the luminance of the pair. Each of the five subjects went through the experiment three times after a certain exercise and their average results were adopted in this paper.

(3-2). Transient response on luminance

The luminance of a pulse pair is shown in Fig. 9 (a) for two positive light pulses, and (b) for a positive and a negative pulse, respectively. The impulse response on luminance was assumed to have an abrupt rise, decreasing gradually afterwards. It was also thought that the largest luminance of two positive pulses occurs at the peak of the second pulse response same as for a sound pulse pair.



(a) Two positive light pulses



(b) A positive and a negative light pulse

Fig. 9. Luminance change of a pulse pair depending on a time interval
(a) Two positive light pulses
(b) A positive and a negative light pulse

From the measured results and the assumptions, Fig. 10 was obtained as the impulse response on the luminance of a light pulse stimulus with the width of 10ms. A thin solid line shows the result of each subject and the thick line shows their average. 1.0 on the ordinate corresponds to the luminance for the comparison single pulse with the magnitude of 10cd/m^2. A negative reaction after a positive one as in the hearing system was not observed. Subjects observed that separation impression for a pair started at 30-45ms for a positive and a negative light pulse and at 30-40ms for two positive light pulses. The distribution of each subject response and the expansion at 50 to 200ms on the impulse response is supposed to be the apparent luminance increase caused by the flickering of the power line frequency. The impulse response for smooth light shift ought to have a monotonous decrease which is shown by a dotted line.

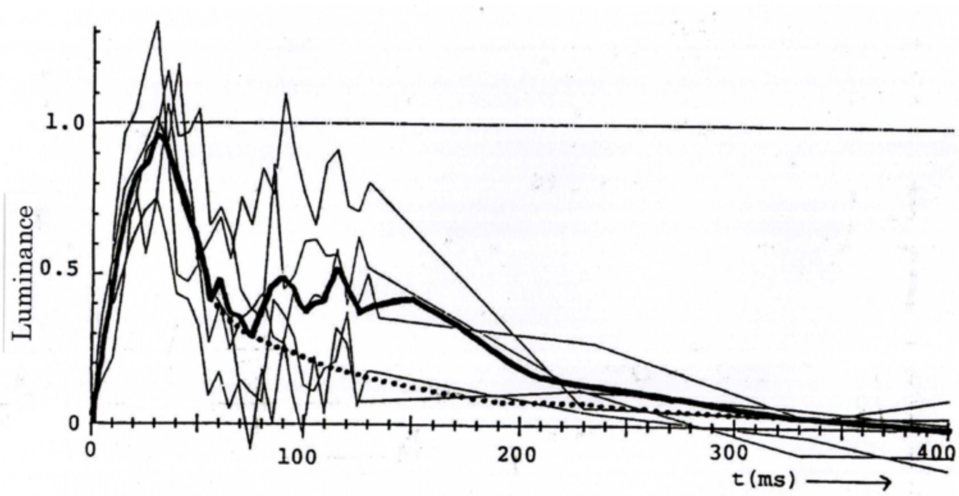


Fig. 10. Impulse responses on the luminance to a light pulse of 10ms width

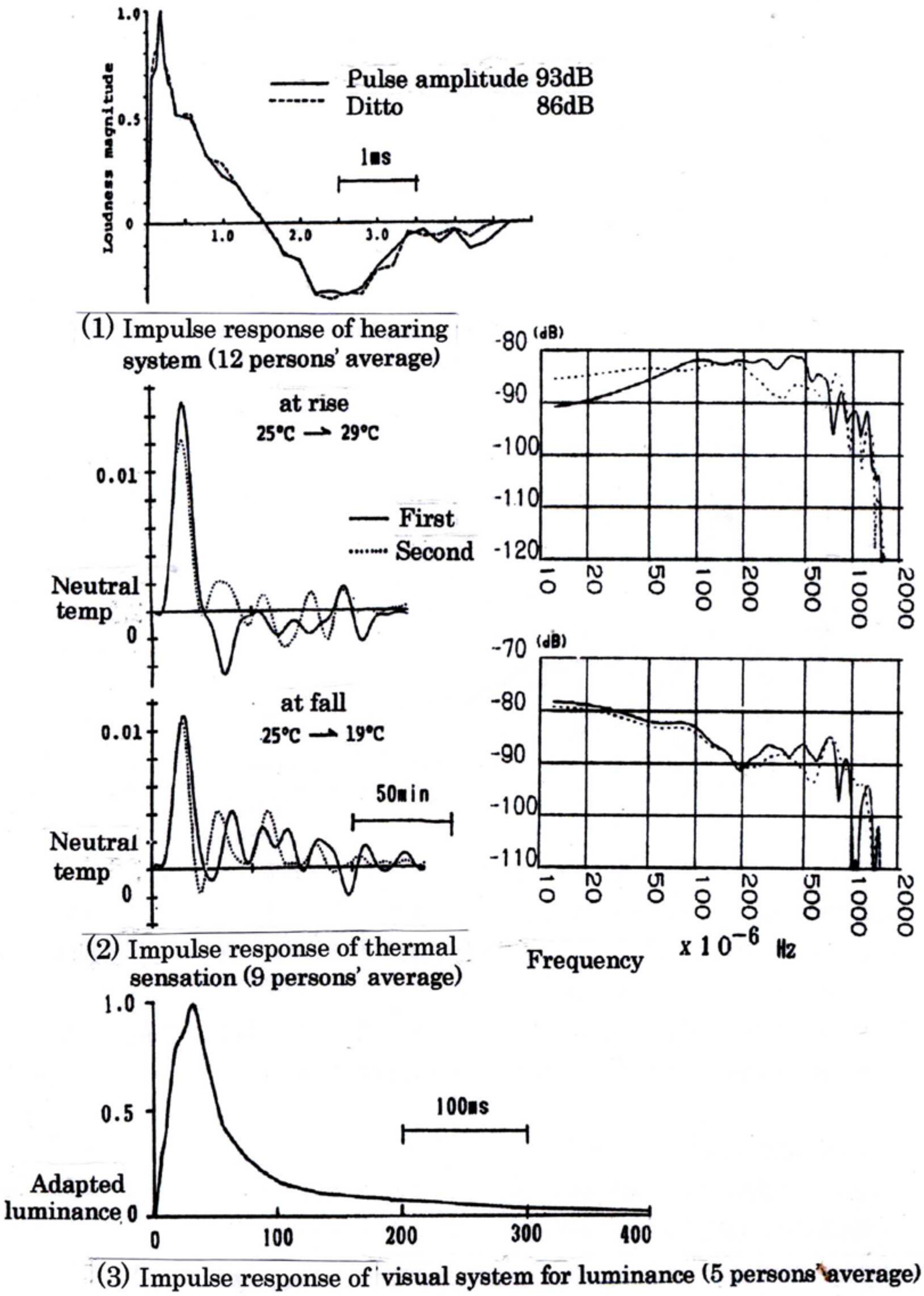


Fig. 11. Impulse response comparison for three different sensory systems

4. Discussion

Thus impulse responses were measured for three sensory systems. Now they can be compared with the same expressions, impulse responses as in Fig.11. There (1) shows the impulse response for loudness, (2) the one for thermal sensation and (3) the one for luminance.

Each impulse response has an abrupt rise and the later response is different with each other. The hearing system has a large negative reaction, and the thermal sensation has shaking reaction in negative and positive. On the other hand, the visual response has a smooth decrease on the positive side. Each impulse response must be measured with more test persons.

The impulse response for loudness finishes around 5 ms, the one for thermal sensation does around 150 minutes and the one for luminance around 400 ms. The frequency characteristics are shown only for thermal sensation in the right of Fig. 11. (2). Any particularly dominant frequencies were not recognized.

If the treatment of each sensory system for further stages is referred with each other and simulated on the other system, each system's evaluation will be improved.

From the region where the linear behavior of each system is distorted and saturated, it starts to show stress. Each sensory system might produce in this region the common substance in the physiology of a human body.

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