# EXPERIMENTAL STUDIES ON AUDITORY ADAPTATION

**B. A. WITTICH**

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L' instinct qui pousse l'homme à chercher la vérité, son besoin impérieux de croire, son inspiration à l'infini sont des faits de nature de l'homme, des faits d'expérience d'où il faut partir et qu'on ne peut supprimer ni changer

Claude Bernard

# EXPERIMENTAL STUDIES ON AUDITORY ADAPTATION

**PROEFSCHRIFT**

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## KORTE SAMENVATTING

Dit proefschrift is het verslag van een studie van de meetbare verschijnselen, die optreden wanneer het oor een continue zuivere toon krijgt aangeboden waarbij zeer spoedig een subjectieve luidheidsdaling waarneembaar is. Onder deze luidheidsdaling, in de litteratuur „Luidheidsadaptatie" genoemd, wordt verstaan de tijdelijke daling in luidheid van een ononderbroken aangeboden acoustisch signaal, waarvan de intensiteit niet hoger is dan 70 tot 80 decibel SPL. Vijf proefpersonen werden in verschillende experimenten getest met behulp van een binaurale lateralisatie-procedure.

Door electrophysiologische experimenten is bekend geworden dat de neurale adaptatie reeds binnen enkele tienden van een seconde is voltooid. In deze studie werd een onderzoek ingesteld naar de snelheid waarmee de subjectieve luidheidsdaling zich ontwikkelt vanaf het ogenblik van aanbieding van de continue toon. Bovendien werd deze luidheidsdaling, als functie van de duur van de continue toon, vergeleken met deze relatie in het electrophysiologisch experiment.

In tegenstelling tot de reeds gevestigde theorie betreffende het dalen van de luidheidssensatie blijkt uit dit onderzoek dat deze daling in de eerste kwart seconde zeer snel verloopt en dat binnen 4 seconden na het begin van de continue acoustische prikkel reeds meer dan 75% van de totale meetbare daling, uitgedrukt in decibels, bereikt is.

Deze experimentele bevindingen wijzen er op, dat de luidheidsdaling als functie van tijdsduur van de continue prikkel gecorreleerd is aan het neurale aanpassingsproces. Verder blijkt de intensiteit van de acoustische prikkel een belangrijke invloed te hebben op de mate van luidheidsdaling, uitgedrukt in decibels. Wanneer er rekening wordt gehouden met het experimenteel vastgestelde centrale maskeringseffect is het zeer goed mogelijk, dat de intensiteit van de prikkel als zodanig een belangrijk groter effect heeft dan de in dit proefschrift gemeten waarden. Het een en ander wordt in een graphische voorstelling vergeleken.

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# I INTRODUCTION

When submitted to a sustained acoustic stimulation with both pure tones and noises man gets the experience that, after listening for a few minutes to the sound, its loudness seems to diminish. This change in loudness sensation has been described in the past few decades by the terms "Auditory adaptation" and "Auditory fatigue" (von Békésy, 1933; de Maré, 1939; Hood, 1949; van Dishoeck, 1953). The two terms were used to indicate the same audiologic phenomenon (Wever, 1949; Hood, 1949; Hirsch, 1952; Jerger, 1956) until the round table conference on this subject at Bonn (1960) introduced a generally accepted uniformity in terminology. It was emphasized in the paper of Zwislocki (relation of adaptation to fatigue, Bonn 1960) that "Auditory adaptation" concerns the loudness decay observed during sustained acoustic stimulation, as well as the threshold shift brought about by this stimulation. The amount of loudness decay and of threshold shift, expressed in decibels, reaches definite values asymptotically. On the contrary "Auditory fatigue", indicating a functional state of the auditory sense organ during or following sustained high intensity acoustic stimulation, includes an alteration of the physiologic process in the auditory end organ. The loudness decay nor the threshold shift in this functional condition never proved to reach definite values.

More than one century ago Dove and Helmholtz (1857) noted that an amplitudinally modulated signal seemed to be louder than a signal of constant intensity equal to the maximal amplitude of the modulated signal. With the aid of two tuning forks one ear was presented a sound of constant intensity and the other ear the sound waves from a tuning fork in a vertical position that was turned around its longitudinal axis. Both tuning forks produced sounds of equal intensity, but the turning fork offered it with maximal amplitudes, four times in one turn. It appeared that the maximal amplitude of the modulated sound was judged to be louder than the sound offered at a constant level. Although the authors neither attributed a sensorineural nor a physiological character to this phenomenon and abstained from giving it a name, in fact this was the first demonstration of "Auditory adaptation".

In sense organ physiology, specifically by electro-physiologic experiments, a decline in the frequency of the discharges of nerve impulses from different end organs was established, which phenomenon was designated "Adaptation" (Adrian et al., 1928). Adrian and Zottermann (1926) recorded action potentials in the nerve fibre to a single Pacinian corpuscle in the foot of the cat. They found that during constant stimulation the activity of the end organ increased immediately after the onset of stimulation and then decreased for the remaining period of stimulation. The initial increase in the activity of the end organ proved to be inversely related to the length of the build-up time of the stimulus, which did not otherwise influence the activity. The effect of the stimulus depended not only on the intensity but also on the rapidity with which it was applied. Thus, a stimulus of slow onset might reach a relatively great intensity without the result of an excitation. This phenomenon must be supposed to be due to a very rapid adaptation of the tissue to the environmental changes. Adaptation as such occurs in motor and sensory pathways as was found by Adrian, who concluded that this phenomenon was strictly comparable to the decreased activity observed in the above mentioned experiment. However, Adrian suggested another possibility which should be considered: "The decline in the frequency of the discharge might perhaps be due to fatigue and not to adaptation. "Fatigue" is a word which can mean so many things that a definition is essential. As used here it means a decline in activity caused by the previous activity of the organ, "Adaptation" meaning a decline in excitability caused by the stimulus — the change in the environment — quite apart from the existence of activity". In the stretch receptor recordings a much great number of impulses during the first 3—4 sec was registered by a rapidly increasing stimulus than by the intermediate increasing ones, but the subsequent decline in frequency was the same for both. If the decline was due to fatigue it should evidently be the greater in the case where there has been the greater initial activity.

Derbyshire and Davis (1935) noted a decrease in the voltage output of the auditory nerve shortly after the onset of acoustic stimulation. A similar observation was made by Galambos and Davis (1943), who, by means of micro-electrode recordings of second order neurons, found a decrease both in the rate and in the amplitude of the discharge. As a general rule both rate- and amplitude-adaptation were completed within a few tenths of a second after the beginning of the nerve response and the name "fast equilibration" is quite appropriate to the phenomenon, that was registered in the first 200 msec. The part of the registered neural discharges in which only small changes in amplitude were seen, is called "slow equilibration". In an elaborate study Coats (1964) confirmed the results of Derbyshire and Davis (1935). He further observed that the amount of depression of the amplitudes is dependend on the intensity of the signal. Up to a level of 60 decibel re 0.0002 microbar this effect is gradually increasing; with greater intensities the depression falls fairly rapid off to a minimum. It was further emphasized in his study that the intensity as such has no effect on the rate of recovery. In contrast increasing duration of the signal significantly slowed the rate of recovery.

Quite recently Greenwood and Maruyama (1965) registered more complex discharge patterns by micro-electrode recordings from the dorsal cochlear nucleus. They noted a reduction of discharge in the socalled nonmonotonic units by increase in stimulus intensity. The conventional picture of adaptation as observed in the whole nerve experiment of Derbyshire and Davis (1935) differs in more than one aspect from the one that reflects the behaviour of the units considered by Greenwood and Maruyama. The presence of



onset response, silent pauses, periods of reduced discharge during response should be taken into account in a complete description of the adaptive properties of auditory neurons.

In contrast to known facts in electro-physiology, in psycho-physiology a two-phase process has not been demonstrated as the underlying mechanism of auditory adaptation. Although much has been written about "Initial adaptation" (Lüscher and Zwislocki, 1949; Rawnsley and Harris, 1952; Bentzen, 1953), a term used to indicate short temporary threshold shifts, these findings have not been associated with data from studies of auditory adaptation during sustained stimulation, but mostly classified under the heading "Masking" (Ward et al., 1963).

Comparing his results to those of Hood, Wright (1960) already suggested that the idea of a relatively slow development of adaptation was no longer tenable. In 1964 Takashi Tsuiki demonstrated his results with a dichotic testing procedure, using the Békésy type audiometry to avoid adaptation of the control ear. He stated that the greater part of the loudness decrease developed in the first few seconds. As a function of the stimulus duration Derbyshire and Davis (1935) described a two-phase course of the over-all action potential discharges from the auditory nerve in response to tonal stimulation. They demonstrated a fast as well as a slow equilibration (= adaptation) process.

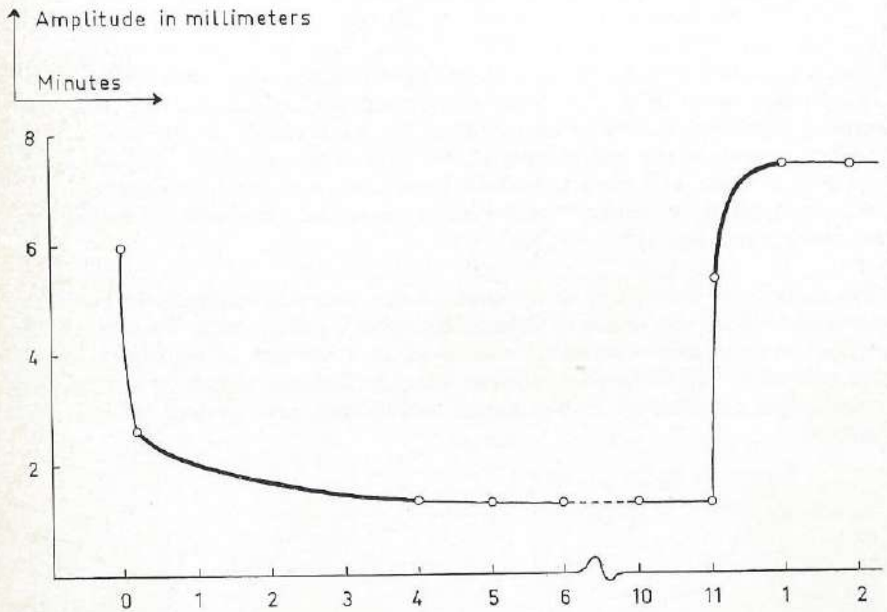



Figure 1 The decrease of the amplitude of the action potentials recorded from the auditory nerve during and after continuous stimulation at 1500 cps shows slow equilibration and recovery. The initial phase of fast equilibration occurred too rapidly to be plotted on this time scale. (Adapted from Derbyshire and Davis, 1935).

However, up to the present time, a fast and a slow adaptation process has not yet been detected in psycho-acoustic experiments. On the other hand, Sörensen (1959) and Spoor (1960) recently correlated their results from electro-physiological experiments with those from psycho-acoustic experiments, in which a brief change in auditory sensitivity to low intensity stimulation with pure tones was measured (de Maré, 1939; Gardner, 1947; Lüscher and Zwislocki, 1949; Harris, 1950; Bentzen, 1953; Schaefer, 1960). Action potentials, recorded from the whole nerve, showed the phenomenon as a decrease of their amplitude. The duration of the interstimulus interval necessary to reproduce the same and maximal amplitude of the section potential, as seen during the very first stimulus, was established. Starr (1965) too suggested a relationship of electro-physiologic findings to similar psycho-acoustic experiments. In his experiments spontaneously active units in cochlear nucleus of anaesthetized cats were studied during stimulation with steady tones for periods ranging from 5 sec to more than 10 min. The recorded aftereffects, demonstrated in the single units in the cochlear nucleus, have several temporal and quantitative similarities to psycho-physical results.

Starting with man's auditory experience of sustained acoustic stimulation, it was stated already that during listening the loudness seems to decay. This decay of a sound during prolonged stimulation as yet can be considered as a subjective experience of the change in the functional state of the auditory sensory system. In the past few decades the loudness decay, within one or two seconds from the onset of the acoustic stimulation as such was studied quantitatively. Davis (1935) doubted the existence of the psycho-acoustic correlate of his electro-physiologic findings when he stated: "There is no suggestion of any auditory experience that correlates with the particularly rapid and extensive equilibration (= adaptation), which occurs in the auditory nerve of the cat at frequencies near 1000 and 2000 cps." Up to the present time we still have the well-known picture of the time-relation of the early adaptation of sensory nerve action potentials but lack its counterpart in hearing (cf. fig. 1).

The purpose of this study is to measure the decay of loudness at sustained stimulation from the onset of stimulation up to its final value. From the slope of the curve of loudness decay measured as a function of stimulus duration, the inference will be made, whether or not loudness decay is the psycho-physiologic counterpart of the electro-physiologic phenomenon of the eight nerve.



## II LITERATURE

In order to measure the decay of loudness sensation during acoustic stimulation a great number of psycho-acoustic experiments has been developed. Referring to the many publications on this subject we have to distinguish two major procedures, each divided in several methods according to their pecularities. This will provide the opportunity of showing which difficulties actually arose and to what extent the imperfection of these procedures limits the reliability of the measurements.

Up to the present time the following procedures for measuring auditory adaptation have been developed:

1. **Monaural procedures** (figure 2)

   **The threshold under masking** (Lüscher and Zwislocki, 1949; Feldmann, 1957; Langenbeck and Kietz, 1959; Schaefer, 1959)

   **The threshold tone decay test** (Carhart, 1957; Bosatra, 1960)

   **Békésy audiometry** (Jerger, 1960)

2. **Binaural procedures** (figure 3)

   **Poststimulatory comparison method** (Pattie, 1927; de Maré, 1939; Wood; van Gool, 1952; Egan and Thwing, 1955)

   **Perstimulatory comparison method,** divided into Simultaneous dichotic balance methods (Hood, 1949) and Localization methods (Wright, 1960).

### Monaural procedures

### Threshold under masking

According to German authors (Langenbeck et al., 1959), this procedure without making use of a comparison or control ear, represents the best way to measure loudness decay specifically in pathological conditions. In the method of Feldmann, i.e. measuring the loudness decay by masking the pure tone stimulation by a white noise, the decrease of the intensity of the masking noise (interrupted) in decibels represents the amount of loudness decay (cf. fig. 2a).

The Kietz-Langenbeck test is a variant of the white-noise threshold audiometry. A sustained pure tone stimulation is masked in the same canal by interrupted white noise pulses 0.4 sec in length with an interval of 0.04 sec. The intensity of the pure tone is varied in one decibel steps until the subject can hear the tone in the intervals (cf. fig. 2b).

In the test procedure of Lüscher and Zwislocki the audibility of a pure tone signal is matched in relation to the masking effect of white noise pulses. In an extensive experimental study Schaefer (1960) used this method in a great variety of parameters (cf. fig. 2c).

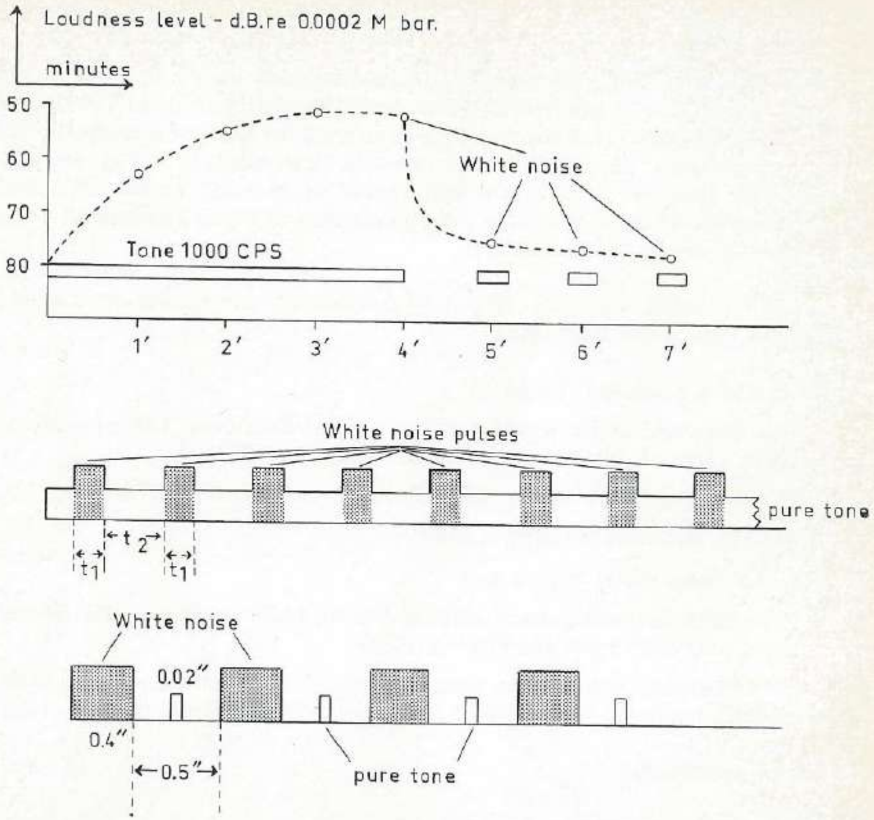



Figure 2a Threshold under masking (Feldmann).
The subject is presented a pure tone and after one minute of sustained stimulation the same ear is offered a white noise during a few seconds, necessary for attenuating the white noise to a level, that permits just hearing the pure tone through the white noise. After four minutes of sustained pure tone stimulation the recovery from this functional state is measured with short duration tones and white noises.

Figure 2b The Kietz—Langenbeck test.
One ear is offered a pure tone (sustained stimulation) together with a series of white noise pulses, of which the duration $t_1$ and the interval $t_2$ can be varied. Durations of $t_1$ and $t_2$ in relation to the intensity of both signals are measured when the pure tone in between the white noise pulses is just above the level of audibility.

Figure 2c Initial adaptation or residual masking (Lüscher and Zwislocki).
The adaptation is measured as a function of the intensity of the pure tone pulse just below hearing level in relation to the interval between white noise and pure tone pulses.

Although we may agree about the usefulness of a monaural procedure for clinical application, we may doubt its importance in measuring the decay of loudness as such.



Concerning the quantitative results of these methods it can be said that the amount of loudness decay as measured by the method of Feldmann and plotted as a function of intensity of the adapting signal appeared to be slowly progressive, depending on the intensity. As the picture (cf. fig. 2a) shows, at 80 decibel re 0.0002 microbar the loudness decay lies somewhere between 20 and 30 decibel, besides a dependence on frequency and band-width of resp. tone and noise. The same can be said of the results of the Kietz-Langenbeck test, but here and in the Lüscher and Zwislocki experiments there are more variables, which influence the results.

Moreover phenomena such as masking and auditory fatigue are identified with loudness decay. Thus it is obvious that in the test of Feldmann, Langenbeck and of Lüscher and Zwislocki different aspects of the change in functional state of the audiotory organ are measured. Therefore these tests are less reliable for detection of pathological conditions of auditory adaptation than the threshold tone decay test, where no masking and fatigue are present.

## Threshold tone decay test

By this procedure the testperson's hearing of a sustained pure tone at near threshold intensity is determined. First, the threshold of the frequency tested is measured by presenting short tone pulses. Then the same frequency is offered as a sustained tonal stimulation, a few decibels louder than the threshold intensity. The auditory sensation of a pure tone as well as the all or non hearing of that tone as a function of duration of the tonal signal are pointed out to the subject. Normally under these conditions a subject is able to hear a pure tone as such beyond one minute of sustained presentation. This test might be considered as the observation of the adaptation in hearing at near threshold intensity, although the word "threshold" evokes the connotation of the very first appreciation of hearing a tone or a sound without the accompanying judgment of a particular loudness. Therefore to call this change in sensation a loudness decay sounds contradictorily and in the literature this phenomenon is not always referred to with the conventional term of "auditory loudness adaptation". However, the threshold tone decay test already proved to be very useful and reliable in the differential diagnosis of perceptive deafness.

## Békésy audiometry

More or less based on the same principle as the threshold tone decay test, the Békésy audiometry can produce diagnostic cues by revealing different rates of loudness decay. Lundborg (1952) in his monograph, dealt principally with the amplitudes of the audiometric tracings. In an attempt to analyse auditory disorders found by Békésy audiometry, Jerger showed that most tracings of 434 Békésy audiograms could be placed into one of four categories (1960). The basis for categorization is the relationship between tracings of periodically interrupted and of continuously tonal stimuli.

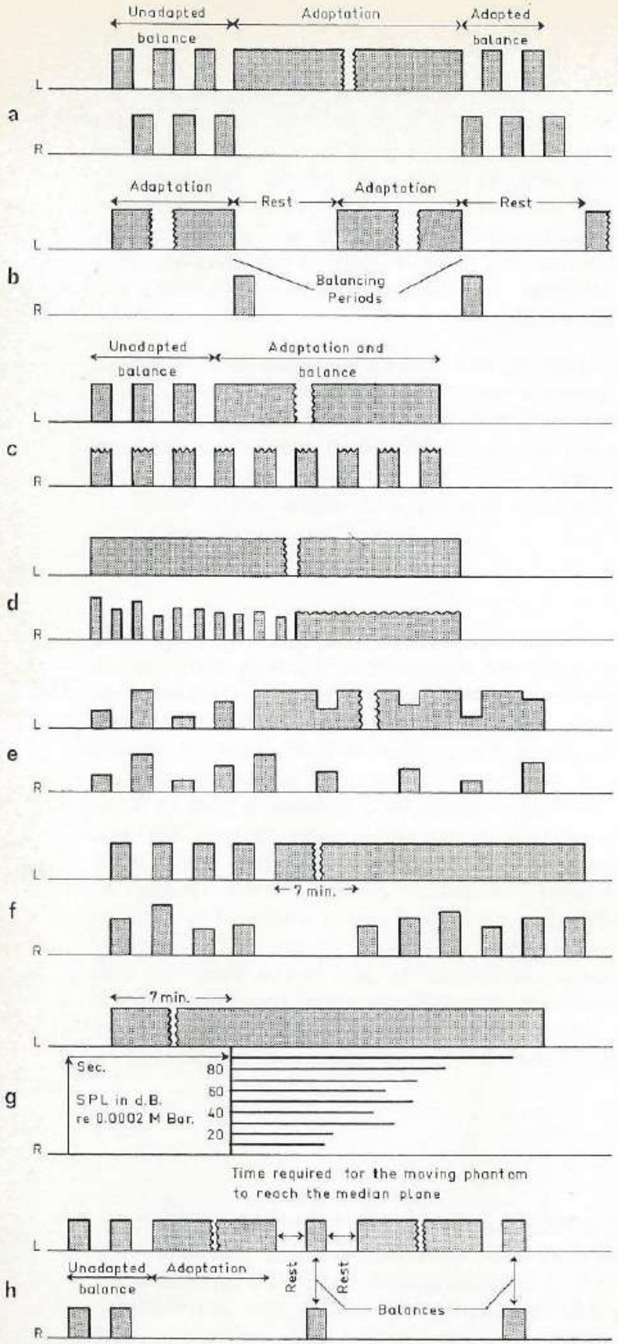



Figure 3 Schematic representations of the binaural procedures.

a. Alternate binaural loudness balance (poststimulatory comparison method), utilized by Pattie (1927), de Maré (1939), Davis et al. (1950), Hood (1950) and Egan and Thwing (1955).

b. Modification of procedure 3a (Wood). There is only one balancing period after the adapting period (Van Gool, 1952).

c. Perstimulatory comparison method. Tracking method of Hood (1949). The intensity of the comparison stimulus is varied continuously in a bracketing fashion, which is automatically recorded. A modification of Hood's method is the balance with comparison stimuli of fixed intensity.

d. Modification of Hood's method. The control ear (R) is offered the same pure tone as the test ear, but interrupted, i.e. one second on — one second off stimulation (Wittich, pilot study, 1960).

e. Perstimulatory comparison method of Egan (1955). The different height of the on-off markers represents the intensity levels at which the adapting stimulus is presented in a simultaneous dichotic balance.

f. Localization methods (Wright, 1960). Both ears are offered pure tones of the same frequency (f = 250, 500, 1000 and 4000 cps). In the initial balance the tones are simultaneously offered to both ears to obtain a median plane localization of the sound image within the head of the subject. After seven minutes of sustained tonal stimulation of one ear, a series of tone pulses is offered to the other ear in order to obtain once more a median plane localization of the sound image.

g. Modification of 3f, the "Moving phantom" (Wright, 1960). A sustained pure tonal stimulation during seven minutes is offered to the test ear and subsequently to the other (= control) ear. Time in seconds necessary for the sound image to travel from the control ear to the median plane is measured.

h. "Intensive and Phase" localization method according to Von Békésy (1929) and Egan and Thwing (1955), which can be considered as a combination of both, post- and perstimulatory procedures.



## Binaural procedures

### The poststimulatory comparison method

In this method the loudness sensations of the acoustic signals at each ear are compared after cessation of the adapting stimulus, i.e. the stimulus causing a decay of loudness in the ear under testing conditions. Generally this technique has been called the "Alternate binaural loudness balance". This method either as described, or in a slightly modified presentation has been utilized by Pattie (1927), de Maré (1939), Davis et al. (1950), Hood (1949) and Egan and Thwing (1955). As the scheme (cf. fig. 3) shows, the subject in a final balance adjusts the intensity of the stimulus to the control ear till equal loudness in both ears is reached.

### The perstimulatory comparison method

This method in advantage to the alternate binaural loudness balance offers the opportunity to study the loudness decay during the presentation of the sustained acoustic stimulation. Following this method two procedures are utilized: Simultaneous dichotic balance and Localisation methods.

### Simultaneous dichotic balance

In this respect we mention the fixed intensity method of Hood (cf. fig. 3) as the most important procedure. After an initial simultaneous balance one ear is submitted to a sustained tonal stimulation, whereas the stimulus to the other ear is varied in intensity in a bracketing way around the one, that gives the impression of equal loudness. A modification of this method was introduced by Egan (1955), who minimized the formation of a loudness standard within the subject. In this procedure a single balance was made each time the control stimulus was presented to the control ear. Every measurement started with a series of single balances, whereas the perstimulatorily matched loudness decay was determined from the average of the initial balance series and the one found during the sustained stimulation period.

### Localization methods

When identical stimuli are presented by earphones to both ears simultaneously they tend to fuse into a single sound image, which is heard in a plane somewhere in or around the head between the ears. On this principle (von Békésy, 1929) Wright (1960) developed the "Median plane localization test". Wright in his experiments used a stimulation period of 7 minutes, which according to him and others is needed to adapt the ear under test condition as to reach a steady state of activity. It has been accepted that beyond this time limit no further change of the functional state of the auditory organ is observed, provided that moderate loudness levels are used in the sustained signal. A modification of this method is the "Moving phantom" procedure (Wright, 1960), in which the time is determined during which the sound image passes to a median plane from laterally when after a sustained stimulation of the test ear the same tone is introduced to the other ear also by a sustained stimulation.

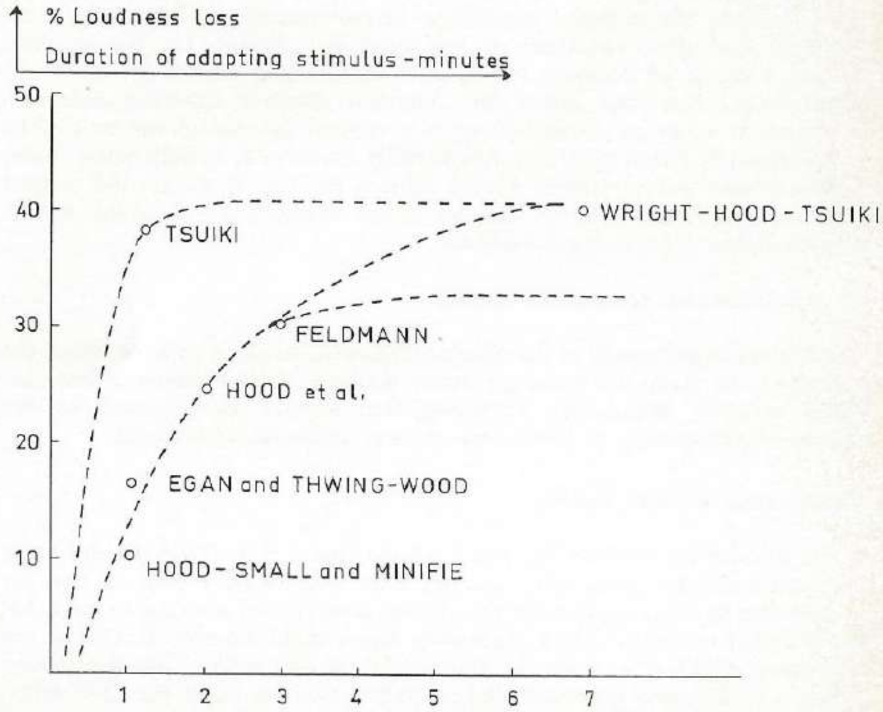



Figure 4 Loudness decay plotted as the function of duration of the conditioning stimulus. On the ordinate loudness decay is plotted as a percentage of loudness loss; values are to be considered as representative for different sensation levels.

Recently Takashi Tsuiki published his investigations with a procedure, which might be called a variant of Wright's method (Copenhagen, VIIth Int. Congress of Audiology, 1964). A pure tone of a given frequency is divided into two channels. The intensity in one of them is constant throughout the test period, the one conducting to the test ear. The other channel through an automatic interruptor and a Békésy type attenuator is passed into the control ear. Thus the comparison tone is interrupted periodically with a repetition period of 2500 msec with a duty cycle of 70%. Both tones are in phase and therefore the phantom sound moves to and fro within the head between both ears in proportion to the interaural loudness differences. The subjects regulate the intensity of the comparison tone by means of a push-button connected to an automatic reversing attenuator of the Békésy type in order to get the phantom sound localized in the center of their head. The results are recorded by a penwriter. Unfortunately no exact figures are given but Tsuiki demonstrated



clearly a considerable amount of loudness decay to occur in the first five seconds.

Von Békésy, Egan and Thwing already used the localization method a few decades ago, to study what they called "Auditory fatigue" (cf. fig. 3). Von Békésy (1929) developed a localization method by means of series of clicks and observed "a shift of the sound image as the result of fatigue......" as he denoted the effect of sound stimulation on the auditory organ. By this procedure he traced the path of the sound images in and around the head. To determine the "amount of fatigue" he used an alternate binaural loudness balance procedure (1933) and demonstrated a faster decay of loudness sensation than all later authors.

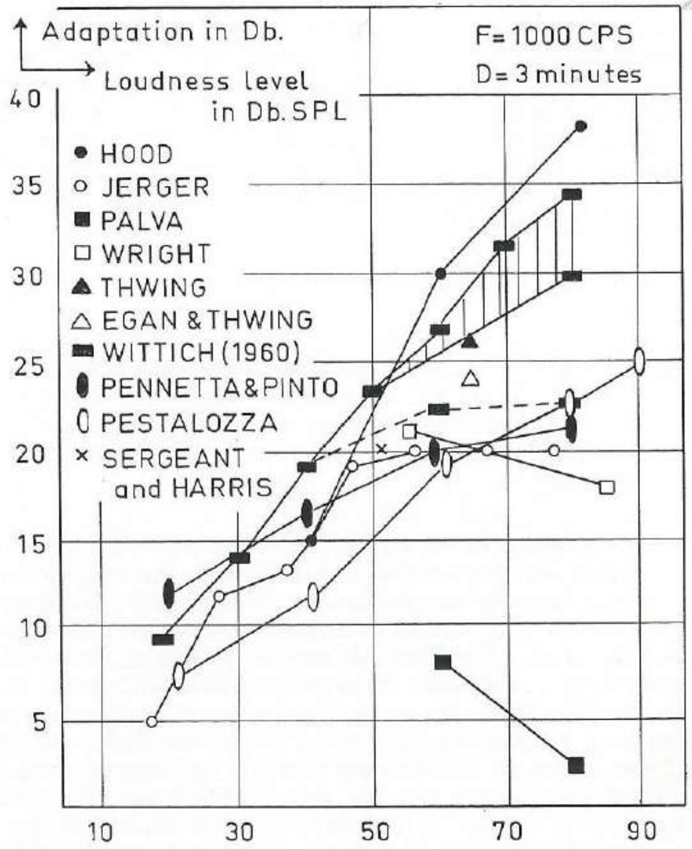



Figure 5 Comparison of results obtained by 10 investigators. All points represent adaptation for a 1000 cps tone after three minutes of sustained stimulation. Our results in a pilot study, as represented by figure 3d, are joined by an interrupted line (1960).

These binaural procedures have been developed to measure the loudness decay during sustained acoustic stimulation by comparison between the subject's both ears. Because of the lack of comparative memory most methods are designed for the indirect way of measuring the phenomenon of auditory adaptation. Disregarding for a moment the different terminology, used by the authors, almost the same loudness decay is derived from all figures as a function of stimulus duration and at different sensation levels (cf. fig. 4). As figure 4 shows, the loudness decay reaches a maximal value after a few minutes in a slow progressive way, the slope of the curve suggesting a rather regular decrease. It should be noted that the results of Tsuiki (1964) are different and suggest another time related function of the loudness decay.

When the results of the most elaborate publications with respect to the amount of loudness decay at different loudness levels are plotted in one picture, we obtain curves, which show a remarkable divergence (cf. fig. 5). Since we can vary the frequency, the intensity and the duration of the adapting stimulus to almost infinite limits, it will be quite clear that a wide variety of methods have established different aspects of the adaptation phenomenon and as can be expected quantitative differences are very striking. It is obvious that the methods and the physical limits of the experimental arrangements are the causes of these discrepancies, because, though differing in terminology, all authors were heading for the same problem.

**General considerations on the binaural procedures**

With regard to the poststimulatory comparison method it ought to be kept in mind that the functional condition of the ear tested is not stable during the final balance, so the authors actually deal with the recovery of the auditory organ from the state of adaptation. Utilizing this method von Békésy already measured a very rapid recovery, his restimulation time for the final balance being only 200 msec.

With regard to the results of the perstimulatory methods we have to compare the results of Hood with those of Palva, as depicted in the scheme of figure 5, and when reading their reports we cannot wonder about their discrepancy. Palva utilized the tracking method in a dichotic stimulation balance with an intensity modulation of 2.3 decibel per second. Hood's experimental results depend on the rapidity of handling the attenuation-knob while bracketing. Both authors used a 10 to 15 sec comparison period on the assumption that only negligible auditory adaptation occurs in the control ear during this time. The results of Palva, however, evidence the contrary and suggest a rapid decay of the loudness sensation in this ear. Wright (1960) tried to minimize the adaptation of the control ear by permitting balance periods of one second only. Concerning Wright's method, which is based on the assumption that the loudness sensations at both ears are equal when the sound image is localized in the median plane of the head, we may agree with the principle used in this method but the evaluation of his measurements is open to objections. In the first place he did not measure early adaptation during acoustic stimulation,



but compared a fully adapted ear, being stimulated for at least 7 minutes by a sound of 90 decibel SPL (sound pressure level), to the control ear. According to most authors this intensity level induces effects of fatigue and not of adaptation in the sense as defined in the first paragraph. Moreover Wright's time measurements are difficult to transform into the more easily handled intensity cues, though his data give information about the temporal course of the development of a steady state of function. His results, however, fully depend on the attention and skill of his subject. The same holds for the experiments of Tsuiki.

**Intensity and frequency of the conditioning stimulus**

About the loudness levels of the sustained tonal stimulation, evidence has been offered that at higher loudness levels the decay of sensation is larger than at moderate and low levels. Up to 80 and 90 decibel re 0.0002 microbar the decay is slowly progressive and from that level upward there seems to be no further decay of loudness. Actually some authors reported a decrease of decay beyond that level, but discrepancies between the various experiments exclude any clear conclusion.

With respect to frequency as a variable, loudness decay has been measured at other frequencies than that of the adapting stimulus. Thwing studied the effect of the spread of auditory adaptation (f = 1000 cps) to neighbouring frequencies. As was confirmed by other authors (van Dishoeck, van Gool, 1953) this spread extends symmetrically around the frequency of the adapting stimulus in contrast to results obtained by psycho-acoustic experiments that deal with effects of fatigue by sounds of high intensity. In the dichotic condition, measuring cross-masking, a same symmetric spread of frequencies was observed by Ingham and Sherrick (f = 250, 500, 1000, 2000 and 4000 cps).

**Loudness function of tones**

Concerning the loudness function of a tone as such, relying on man's thoroughly trained sense of auditory discrimination Helman and Zwislocki (1964) proved that certain observers are capable to assign numbers to psychologic magnitudes not only on a relative but also on an absolute scale.

**Intermittent tones**

Using intermittent acoustic signals, pure tone pulses, clicks and white noise pulses, changes in threshold sensitivity have been measured in a great number of combinations of stimulus duration (adapting period) and interstimulus interval (recovery period) (de Maré, 1939; Carterette, 1955; Lüscher and Zwislocki, 1947; Schaefer, 1959; Langenbeck, 1960; Sherrick and Mangabeira-Albernaz 1961; Small and Minifie, 1961; Sergeant and Harris, 1963). In these publications the influence of the on/off time ratio of the adapting or test stimulus in relation to the measurable threshold shift comes to the fore. The decrease of the threshold sensitivity, expressed in decibels over the normal threshold could be measured. Names as "Initial adaptation", "Short duration fatigue" and "Residual masking" were accepted for the same audiologic phenomenon (van Dishoeck, 1953). However, in these studies a property of the auditory sense organ is described closely related to threshold measurements under the heading "Temporary threshold shift" (Ward, Bell and Fairbanks, Hirsh and Bilger and others, 1961, 1963). These studies together with the investigation on auditory fatigue and masking procure information about changes in ability to distinguish a particular auditory signal, but they do not give clear information about the functional state of the auditory organ "while" listening to a particular acoustic signal. Furthermore it is very difficult in psychometric experiments to catch the subject's appreciation of any auditory experience during a fraction of a second.

Summarizing the literature on auditory adaptation it can be stated that although man is capable of comparing loudness sensations of both the same and different acoustic signals with each other, the decay of loudness sensation under these different conditions is insufficiently clear to allow him to give direct information about it, even when using both ears in this comparison. Therefore, measuring the decay of loudness by some or other phenomenon in a dichotic procedure, with the testing ear kept active by a sustained sound stimulation and the other ear used for reference or standard, might procure more and perhaps quantitative information about this decay, its early rate of development, its rise to its maximum value and the return from this state to the prestimulation condition.



## III EXPERIMENTS

As was said before, the purpose of the experimental study was to measure auditory loudness adaptation in the first few tenths of a second after onset of the tonal stimulation, as well as during gradually larger periods of stimulation until no further loudness adaptation can be experienced.

The method of measuring the loudness decay during sustained acoustic stimulation used in this study is based upon the assumption that in simultaneous dichotic presentation of identical pure tones of equal loudness the sound image is localized in the median plane of the head, provided that the ears have the same auditory threshold.

In a pilot study (cf. fig. 6) it appeared very difficult to measure the loudness decay at the end of a sustained acoustic stimulation period because the experimental results failed to procure consistent figures. Therefore an experimental arrangement was developed in which it was tried to keep the functional state of the ear being tested stable to such an extent that it could no more seriously bias the value of the results. This was carried out by introducing a short pause between the first tonal stimulus (= test stimulus) and the second, dichotically presented, stimulus (= control stimulus). This introduced into the experiments revealed the influence of the length of the interstimulus interval on the measurable amount of loudness decay.

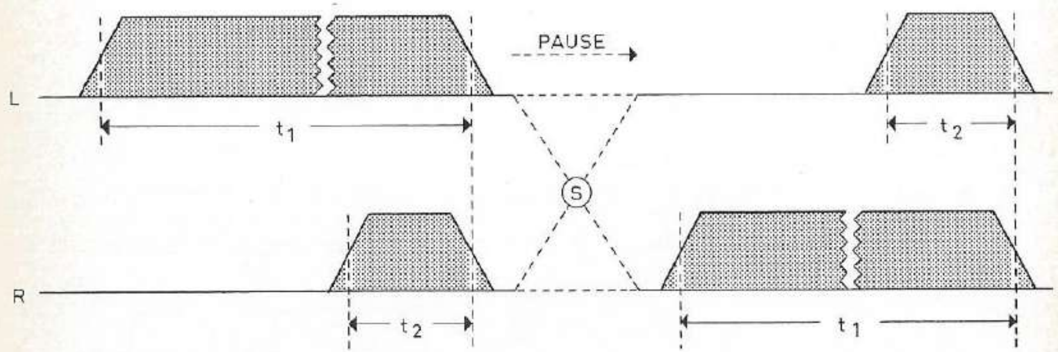



Figure 6 Preliminary experiment with a binaural stimulation procedure. The left ear is presented a pure tone ($t_1$), which length is varied from 1 to 13 seconds (f = 2000 cps). The same frequency is offered by $t_2$ to the other ear, which lenght varied from 0.5 to 2 seconds. After a pause the same program was offered starting with the right ear. The subject had to localize the sound image of $t_2$, which was heard somewhere in the head.

### Testing procedure I (poststimulatory)

A pure tone of a particular moderate loudness level (33, 53 and 73 decibel SPL) is presented to one ear. After a short pause this particular pure tone is presented to both ears simultaneously, while the experimenter attenuates

the signal to the ear not yet stimulated before. After a pause, which permits full recovery the same program is offered starting with the other ear (diagram in fig. 7).
The testperson, with both ears tested, is asked to put down the localization of the sound image of the dichotic stimulation in relation to the median plane of his head. The test procedure was an alternative forced choice type in which the observer had to choose between "crossed" and "uncrossed" if the sound image was localized between the ear not tested or the ear tested and the

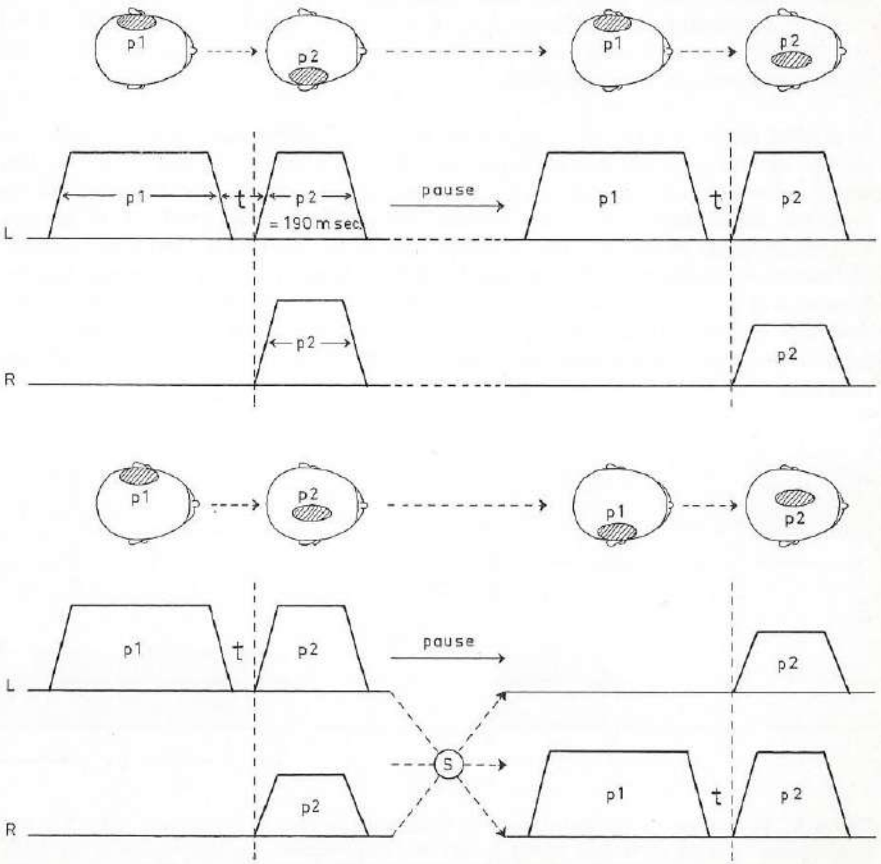



Figure 7 Scheme of the development and application of the testing procedure. The shaded areas represent the localization of the second tone ($p_2$) in the head of the subject. The relative intensity level of the signals are represented by the height of the trapezia. The uppermost scheme represents the basic principle of the procedure, the attenuation of $p_2$ at the right ear to obtain a localization of $p_2$ near or with-in the median plane of the head. To accomplish a forced choice series of trials and to facilitate the judging of lateralization both ears are offered the same program with the same attenuation of $p_2$ (at the control ear) in order to give the answer "crossed" or "uncrossed". In the experimental example of this scheme the lateralization has to be called crossed. The lengths of $p_1$, of $p_2$ and t are measured at half the height of the trapezia.



median plane respectively. In order to give an impression of the median plane, that may happen to lie slightly asymmetrical, specifically in the 33 decibel experiments, the subjects were first offered repetitive dichotic pure tones ($p_2$ in the diagram) simultaneously. Thereafter the subjects proved to be able to indicate the median plane by pointing with a pencil. This trial was also used to see if the earphones were well fitted. After this a test session was started. During the trial the subject could use a pencil, which he used for writing down the symbols for "crossed" and "uncrossed", to point out the place in the head where the sound image was heard after testing of the first ear by the paired program; this in order to compare the two localizations at their best.

The approximate range of intensities of the short second tone ($p_2$) inducing a nearby median plane localization was offered at random at a one decibel difference scale. In a pilot study, using three subjects, the loudness levels for $p_2$ were varied to obtain a clear judgment of lateralization either crossed or uncrossed. With the intensity ratios between the signals of both ears fixed according to the judgment of these three subjects, eight intensity ratios were choosen — in one decibel intervals — which comprised the fixed ratios for crossed and uncrossed lateralizations. The eight values were randomized according to a latin square so that the ratios occurred eight times for each ear. Each mean value of the decay of loudness sensation during one of the many experimental conditions was obtained by 128 (2 times 64) judgments of lateralization.

### Frequency

To prevent the experiment being hampered by the effects of interaural phase differences a pure tone of 2000 cps was used, since tones of frequencies above 1500 cps are localized exclusively by the intensity criterion (Schmidt, 1955; Mills, 1960).

### Intensity of the signal

Three signal levels were choosen: 33, 53 and 73 decibel SPL (sound pressure level) re 0.0002 microbar. For the mere sake of simplicity the intensity of the signals, in the next pages, will be indicated only by the amount of decibels re 0.0002 microbar. With these sound pressure levels three rather different loudness levels were studied on their effect. We avoided the high level of SPL where the stapedius reflex could interfere with the data. In order to prevent overhearing at the 73 decibel level, in one series of trials soft rubber earplugs were connected to the earphones by short plastic tubes (Zwislocki, 1953).

### Duration of the first stimulus ($p_1$)

As stimulation time of the first tone ($p_1$) seven periods were choosen: ¼, ½, 1, 2, 4, 8 and 16 seconds. This choise was based on experimental data from a special pilot study, in which information could be obtained about the rate of loudness decay during sustained tonal stimulation. It offered a good scheme for statistic analysis at that. Together with a limited program of duration periods of one, three, five and in a few trials of ten minutes, these times were offered at random during one test session.

### Duration of the second stimulus ($p_2$)

The duration of the dichotically presented second tone based on the investigations of von Békésy (1939), Bentzen (1953) and Miskolczy—Fodor (1959) was fixed at 190 msec, in order to ascertain the largest loudness sensation together with the least possible adaptation effect. As interstimulus intervals (t) pauses of 20, 40, 80 and 160 msec duration were used.

As intertest-intervals ("pause" in the diagram of fig. 7) periods of rest were offered, which were twice as long as the duration of the first stimulus ($p_1$).

In order to avoid audible transients, the rise- and decay-times of $p_1$ and $p_2$ were always longer than 15 msec. If t was 40 msec and more, rise and decay time were 33 msec, in case t was 20 msec, rise and decay times amounted 17 msec.

### Subjects

The testpersons were five inexperienced subjects with normal auditory threshold, as measured by both continuous and octave audiometry.

### Equipment

All experiments were done with the aid of the electronic equipment of the electro-acoustic laboratory of the E.N.T. clinic at the University Hospital at Leyden. All testing programs were offered to subjects seated in a quiet anechoic room. Figure 8 shows the blockdiagram of the experimental set-up. One tone-generator delivered a 2000 cps tone to both pulse generators I and II. A time switch, automatically and manually controllable, generated trigger pulses, which were fed to pulse generator I, which delivered the first tone pulse. Pulse generator I delivered a trigger pulse to a time delay circuit, which on its turn triggered pulse generator II. The pulses leaving both pulse generators were filtered by narrow band filters. The pulses from pulse generator I were led to a mixing amplifier and attenuator I. The pulses from pulse generator II were led to both mixing amplifiers and attenuators I and II. The attenuation could be regulated in one and five decibel steps.

From the attenuating apparatus the pulses were offered to a pair of moving coil earphones (Standard Cables & Telephones type 4026a). Calibration of the output of the amplifying and attenuating apparatus I and II was done before each experimental session.



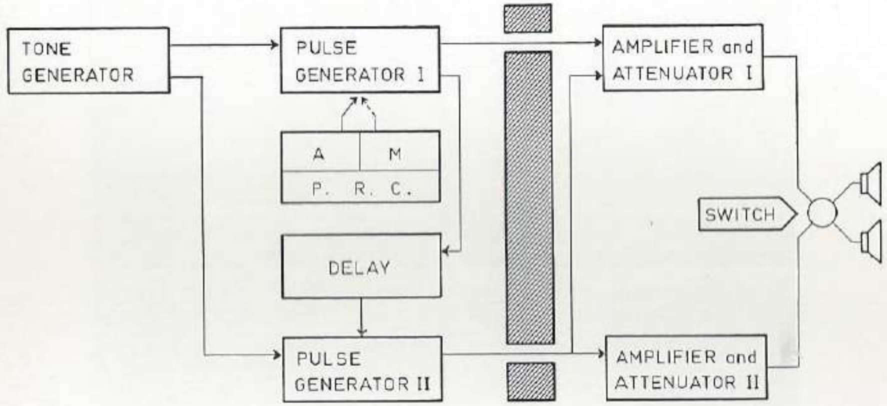
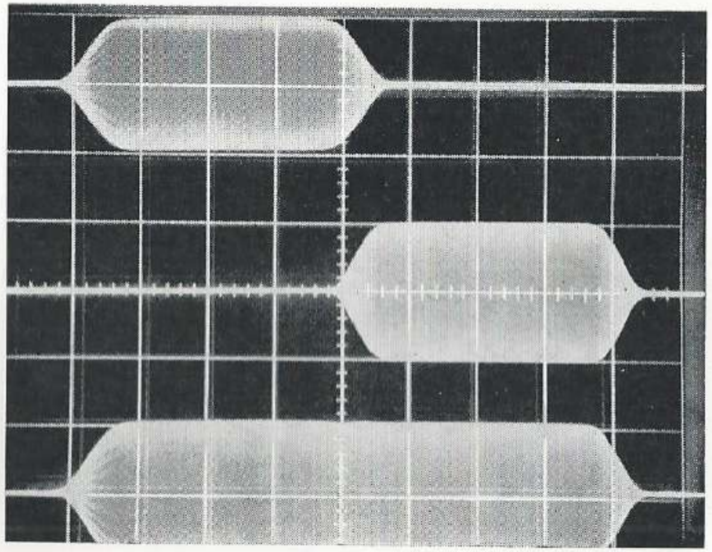



Figure 8 Electronic equipment. A and M together with P R C are the symbols for the automatical or/and manual pulse rate control systems. The shaded area represents the wall of the quiet room.

The pointers on the Volume-Unit meters were set at the same figure during calibration and testing. In this arrangement the output of the whole circuit, including the two earphones, was calibrated on the Brüel and Kjaer frequency analyzer (type 2105) and the artificial ear (type 4109). When calibrating the output of the earphones in decibels SPL the intensities of the signals proved to be 3 decibels above the value of attenuating setting. So a tone of 50 decibel attenuating setting actually had an intensity of 53 decibel re 0.0002 microbar. Signals were passed also through an oscillograph on which the time duration of the stimuli could be controlled and calibrated.

### Testing procedure II (perstimulatory)

The experimental set-up practically is the same as in the poststimulatory procedure except that no pause is introduced between test and control stimuli. In a pilot study we already used a testing program (cf. fig. 6) that did not procure consistent lateralization judgment. The subjects were troubled by the overshooting effect of the short tone pulse ($t_2$ in fig. 6), which seemed to give blurring of localization within their head. This effect was very pronounced when short duration periods of the test stimulus were offered, i.e. the periods of the test stimulus, which are the most interesting in the present investigation. So, after the easily noticeable lateralizations in the poststimulatory conditions we were confronted again with the perstimulatory procedure (cf. oscillographic picture on p. 26). Subjects were well trained listeners then, and the results were far more consistent than we expected and besides that very surprising from the viewpoint of influence of loudness level (cf. § IV).



Oscillographic picture of the stimuli. The signal in top of the screen represents the first stimulus as an isolated pulse offered in order to calibrate its duration in milliseconds or seconds. The signal in the middle represents the second stimulus ($p_2$), always 190 msec in duration. The signal at the bottom of the screen represents the first stimulus ($p_1$) together with the second (= control) stimulus ($p_2$) summated in their rise and decay courses to one signal, which is fed to the test ear. The oscilloscope was a Tektronix type 564.



## IV RESULTS OF THE POSTSTIMULATORY PROCEDURE

### Loudness as a function of duration of the tone stimulus

In order to compare the different values of loudness decay obtained after various stimulation periods, we tried to determine the point, at which — during acoustic stimulation — the beginning of the loudness decay could be revealed by our testing procedure. The experiment, moreover, offered the opportunity to test the validity of our procedure in relation to the findings of Von Békésy, Miskolczy—Fodor and Bentzen with respect to the time duration of the stimulus necessary to produce a maximal loudness sensation.

As von Békésy already established in 1929 the loudness of a tone develops immediately after its introduction into the ear and increases with its duration up to a limit, that he estimated at 0.18 sec. He worked with tones well above threshold. Although his statements are not too clear with respect to the experimental conditions, his conclusion was confirmed by other investigations, which seem to be more elaborate (Miskolczy—Fodor, Bentzen).

### Experiment I

Testing the validity of the procedure with respect to the maximal loudness sensation produced by a tone of a certain intensity.

As intensities were choosen the 33, 53 and 73 decibel loudness levels, the same values as planned for the experiments. Interstimulus interval of the program was fixed at 40 msec in three and at 20 msec in one trial. In this experiment the duration of the first tone was varied from 150 to 175 and 200 msec in a random order. Four subjects were submitted to these trials.

| $Tp_1$ | I = 33 dB | I = 53 dB | I = 73 dB |
|---|---|---|---|
| 150 msec<br>t = 40 msec | — | 6 | 8.5 |
| 175 msec<br>t = 40 msec | 17 | 20 | 28 |
| 200 msec<br>t = 40 msec | 51 | 55 | 61 |
| 200 msec<br>t = 20 msec | 54 | 58 | 64 |

The figures of table I represent the percentage of judgment of sound image lateralization (of $p_2$) between the median plane and the ear not tested by $p_1$. The intensity of $p_2$ at both ears was kept constant and equal to the intensity of $p_1$. The figures represent the judgments of lateralization that need a compensatory attenuation of $p_2$ at the not tested ear to hear both lateralizations of the $p_2$-sound image (of each double testing trial) at one place in the head. I = intensity.

Table I shows at which time duration op $p_1$ no loudness decay could be observed, and moreover that at a 200 msec duration of $p_1$ a definite decay was indicated by judgments of lateralization. Although no quantitative data were obtained, being beyond the purpose of this experiment, we may state that between 150 and 200 msec the first tone reaches its maximal loudness, and that the loudness decay may be detected already at 200 msec after the onset of the stimulation.
We may point out that with our testing procedure the findings of von Békésy and others were confirmed and that this procedure appeared to be appropriate for these findings to be used as a reference level in the evaluation of results.

**Experiment II**

Loudness decay as a function of intensity of $p_1$

The two loudness levels of $p_1$ — 53 and 73 dB — were explored with an interstimulus interval of 40 msec. Table II represents the mean values obtained by trials on five subjects. Although the measured loudness decay shows a divergent trend between both intensity levels up to a 2000 msec stimulation period, the decay of both levels seem to reach the same maximal value.

| $Tp_1$ sec | I = 53 dB | I = 73 dB |
|---|---|---|
| ¼ | 4.8 dB | 4.8 dB |
| ½ | 5.3 | 5.9 |
| 1 | 5.7 | 7.1 |
| 2 | 6.5 | 9.4 |
| 4 | 8.8 | 10.9 |
| 8 | 9.9 | 10.8 |
| 16 | 11.2 | 11.5 |
| 60, 180 and 300 | 11—12 | 12—13 |

Table II Loudness decay, measured after 40 milliseconds interstimulus interval. $Tp_1$ is duration of $p_1$ in seconds. Five Subjects.

For each experiment (table II to VI) the variance between the k subjects was calculated per $Ip_1$ for each value of $Tp_2$ *. As for each experiment these variances do not differ at the 5% level of significance and also do not show any trend for increasing values of $Tp_2$, they can be combined experimentwise. The combined variances do not differ between experiments at the 5% level of significance and consequently they also can be combined. This procedure results in an "overall" variance $s^2 = 0{,}1543$, with 180 degrees of freedom. The standard deviation $s = \sqrt{0{,}1543} = 0{,}38$ characterizes the precision of each value in the tables II-VI. As these values are the means $\bar{x}$ of k subjects, 95% confidence limits can be calculated by using the expression

$$\bar{x} \pm 2 \frac{s}{\sqrt{k}} .$$

If, for instance, $\bar{x} = 9$ and $k = 3$, these limits are $9 \pm 2 \frac{0{,}38}{\sqrt{3}}$, i.e. $9 \pm 0{,}44$.

* Statistical analysis of the data has been carried out under the direction of Drs. H. de Jonge, Head of the medical statistical department, to whom we express our gratitude.



The graphic representation (cf. fig. 9) demonstrates how the 73 dB curve reaches the maximal loudness decay almost within a 4 sec stimulation period, whereas the 53 dB curve reaches the same maximum more gradually. The one, three and five minutes periods of stimulation show but slight changes in the decay, but never exceed the plotted values in the graphic representation. Considering the divergent trend of the two S-shaped curves the question arises whether, although they reach the same maximal value, the higher intensity of the 73 dB signal as such can account for the quicker rise of its curve? In order to obtain clear pictures of the temporal course of the measured loudness decay all curves were plotted on a time-log scale.

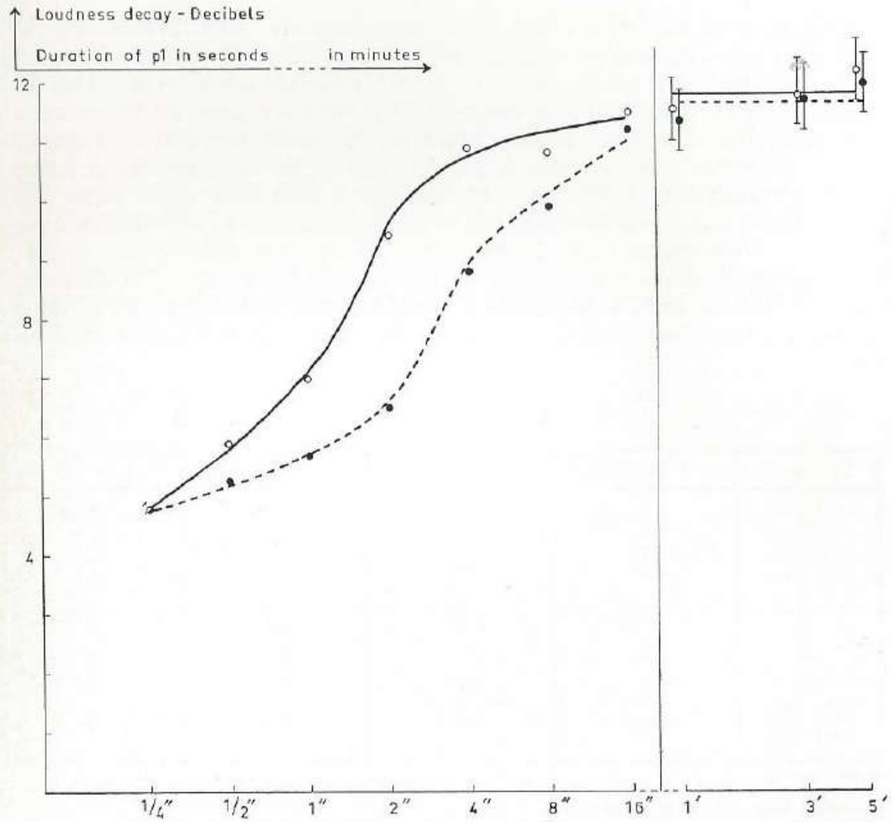



Figure 9 Loudness decay measured as a function of duration of $p_1$.
Interstimulus interval (= t) is 40 milliseconds.
It should be noted here that the values at $Tp_1$ = 10 min. are the same as at $Tp_1$ = 5 min.
Parameters: 73 dB O———O; 53 dB ●·········●

To be sure that the differences between the values at 1, 2 and 4 seconds are not just a matter of chance, the results were submitted to the method of variance-regression analysis. By this statistical calculation the differences proved to be far beyond the experimental error, and definitely significant. So the question arises in which aspect or measurable phenomenon the 73 dB level differs from the 53 dB. Because of the possibility of the interstimulus interval having a great influence on the rate of recovery to prestimulation conditions, it appeared of great importance to vary this entity in another series of tests.

**Experiment III**

Loudness decay at 53 and 73 dB loudness levels measured after interstimulus intervals of 80 and 160 msec.

To measure the influence of the interstimulus interval upon the recovery rate two subjects of the second experiment demonstrating the greatest consistency in their judgments were choosen. The program was the same as in the second experiment, but instead of 40 msec 80 and 160 were used as interstimulus intervals and offered at random. Table III represents the mean values and figure 10 shows their curves. A parallel rise in the four curves is clearly noted although the 73 dB curves tend to rise a little faster. This experiment learned how fast the measurable loudness decay decreases when the recovery time (= interstimulus interval) increases and that the phenomenon appears to be dependent on the intensity of the signal. Apart from this difference between the 53 and 73 dB curves it should be noted that the rate of return to the prestimulation condition seems to be rather constant in both loudness levels.

| Tp₁ sec | A: I = 53 dB | A: I = 73 dB | B: I = 53 dB | B: I = 73 dB |
|---|---|---|---|---|
| ¼ | 1.8 dB | 2.6 dB | 0.7 dB | 2 dB |
| ½ | 2.2 | 3.1 | 1 | 2.2 |
| 1 | 2.3 | 3.8 | 1.5 | 3.1 |
| 2 | 3 | 4.3 | 1.9 | 3.7 |
| 4 | 4 | 6.2 | 2.5 | 4.8 |
| 8 | 4.8 | 6.8 | 4.1 | 5.7 |
| 16 | 6.4 | 7.6 | 4.8 | 6.1 |
| 60, 180 and 300 | 6—7 | 7—8 | 5—6 | 6—7 |

Table III Loudness decay, measured after 80 (List A) and 160 (List B) msec interstimulus interval. Two subjects.

Because this experiment provided a number of data about the influence of interstimulus interval on the amount of measurable loudness decay, we decided to a further study of this point. In the following series of experiments the effect of different loudness levels and stimulation periods upon loudness decay is studied after 20 msec interstimulus interval. This was done in order to minimize the recovery process of the active functional state of the auditory organ to its prestimulation condition.



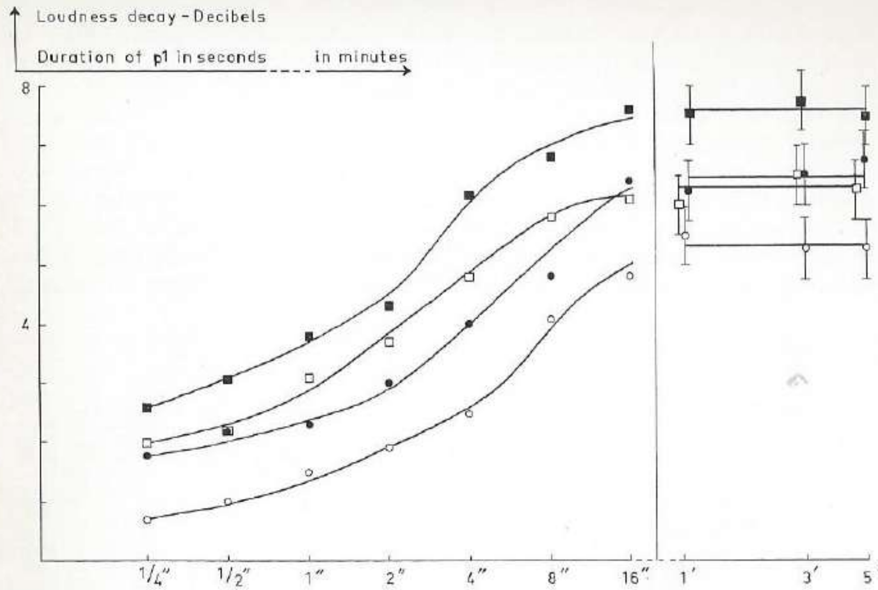



Figure 10 Loudness decay as a function of duration of $p_1$, measured after two different interstimulus intervals.
Parameters: intensity of $p_1$ and interstimulus interval.

■——■ $p_1$ = 73 dB t = 80 msec
□——□ $p_1$ = 73 dB t = 160 msec
●——● $p_1$ = 53 dB t = 80 msec
○——○ $p_1$ = 53 dB t = 160 msec

**Experiment IV**

Effect of intensity and duration of $p_1$ upon loudness decay, measured after 20 msec interstimulus interval.
To evaluate the possible relationship of intensity and duration of $p_1$ with the

| Tp₁ sec | I = 33 dB | I = 53 dB | I = 73 dB |
|---|---|---|---|
| ¼ | 2.5 dB | 3 dB | 3.8 dB |
| ½ | 4.3 | 5.1 | 4.8 |
| 1 | 5.8 | 6.2 | 7.1 |
| 2 | 7.1 | 8.0 | 8.4 |
| 4 | 7.7 | 9.1 | 9.4 |
| 8 | 9.5 | 10.2 | 10.8 |
| 16 | 11.1 | 11.1 | 11.5 |
| 60, 180 and 300 | 10,5—11,5 | 12 | 12 |

Table IV Loudness decay, measured at three different loudness levels. Interstimulus interval is 20 msec. Three subjects.

shortest pause applicable in our experimental set-up, we offered three subjects the test program at the three loudness levels, 33, 53 and 73 dB. The interstimulus interval of 20 msec can be assumed to remain just beyond the limit of interference by audible transients.
The results are listed in table IV and the mean values are plotted in the graphic representation of figure 11. The curves seem to be more linear and of steeper slope than the curves of the 40 msec group (of experiment II), although the same maximal amount of loudness decay is reached within the same time. The 33 dB signal, however, appeared to show a distinct difference between its plotted points and the points of the 53 and 73 dB signals. By using stimulation periods over 16 sec duration period a difference between

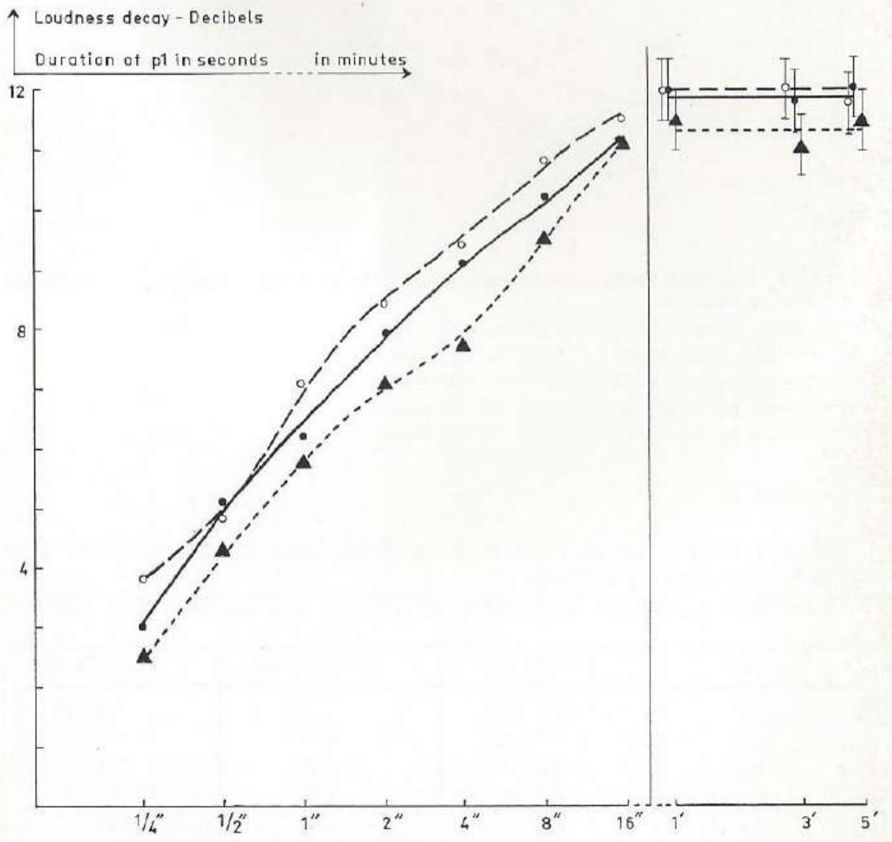



Figure 11 Comparison of loudness decay at different loudness levels of $p_1$ observed after 20 milliseconds interstimulus interval.
Parameters: intensity of $p_1$
O- - -O $p_1$ = 73 dB
●——● $p_1$ = 53 dB
▲- - -▲ $p_1$ = 33 dB



their maximal loudness decay of about one decibel is found, which will be referred to in the next paragraph. A surprising fact in the 20 msec interstimulus interval trials is the rather steep onset of the curves, demonstrating a smaller decay in the first periods.

**Experiment V**

Effect of a 73 dB intensity upon loudness decay when using a pair of sthethosphones.

In order to study the effect of overhearing by air- or bone conduction between the ears, we offered the program with a 73 dB intensity and a 20 msec interstimulus interval under the requirements of interaural insulation to the same three subjects of experiment IV. Table V represents the mean values.

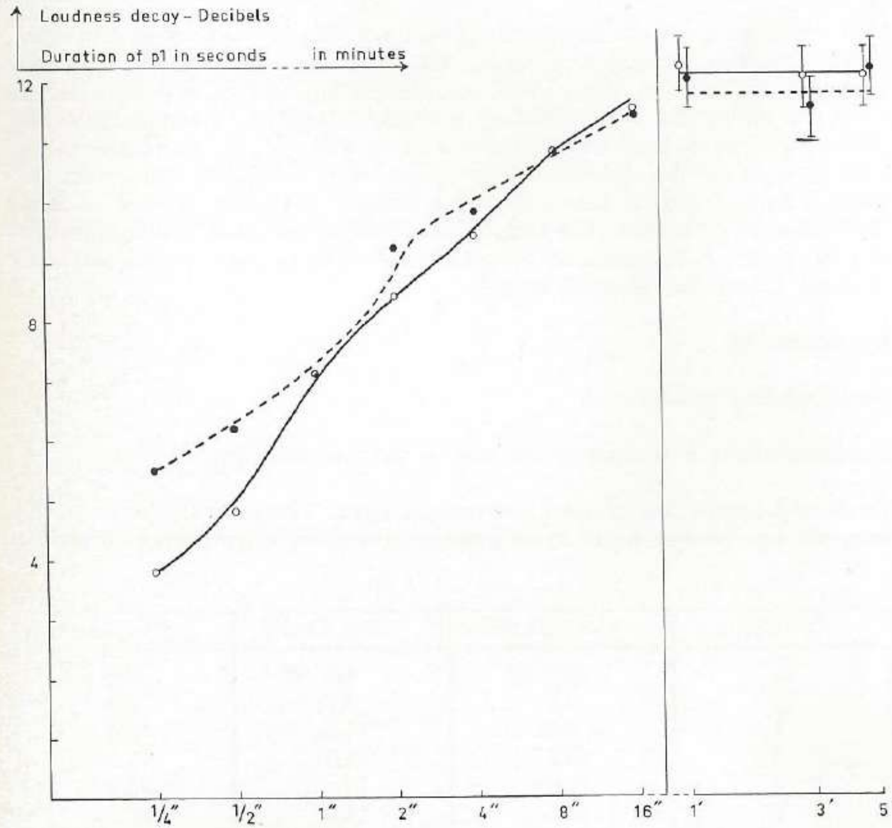



Figure 12 Comparison of loudness decay at a loudness level of 73 dB SPL, measured with and without interaural insulation.
t is 20 msec.
● - - - ● with a pair of sthethosphones.
O——O without (same curve as in figure 11).

| $Tp_1$ sec | * I = 73 dB | I = 73 dB |
|---|---|---|
| ¼ | 5.5 dB | 3.8 dB |
| ½ | 6.2 | 4.8 |
| 1 | 7.1 | 7.1 |
| 2 | 9.2 | 8.4 |
| 4 | 9.8 | 9.4 |
| 8 | 10.8 | 10.8 |
| 16 | 11.4 | 11.5 |
| 60, 180 and 300 | 12 | 12 |

Table V Comparing the results of a trial with a part of sthethosphones (*) and a trial with the common earphone fitting. Three subjetcs. Interstimulus interval is 20 msec.

In the graphic representation (cf. fig. 12) we note a remarkable difference of the first two stimulation periods. From 1000 msec on the two lines fuse to end at the same maximal value, but the 250 and 500 msec plots show an important difference, that should be analyzed. It should be suggested firstly that acoustical leakage between the ears in the common earphone set-up may account for the difference, but in that case we should expect the difference to be equal at every following stimulation period and not to show the fusion of the curves. The assumption might be ventured that it reflects a central effect, independent of the acoustical leakage between the two ears (Ingham, Chocholle, Sherrick et al.).

**Experiment VI**

Perstimulatory condition

Loudness decay measured at the end of the first stimulus.

To three subjects, two of them well trained by the foregoing experiments, the program was offered at all three intensities. Signals were calibrated on the

| $Tp_1$ sec | I = 33 dB | I = 53 dB | I = 73 dB |
|---|---|---|---|
| ¼ | 5.7 dB | 5.6 dB | 6.6 dB |
| ½ | 6.7 | 8.1 | 9.9 |
| 1 | 8.8 | 11.3 | 15.4 |
| 2 | 10.2 | 12.3 | 17.5 |
| 4 | 11.8 | 14 | 20.2 |
| 8 | 12 | 14.2 | 22.3 |
| 12 | — | — | 23.4 |
| 16 | 12 | 14 | 23.2 |
| 60 | 12 | 14 | 23—24 |

Table VI Perstimulatory procedure. Three subjects.



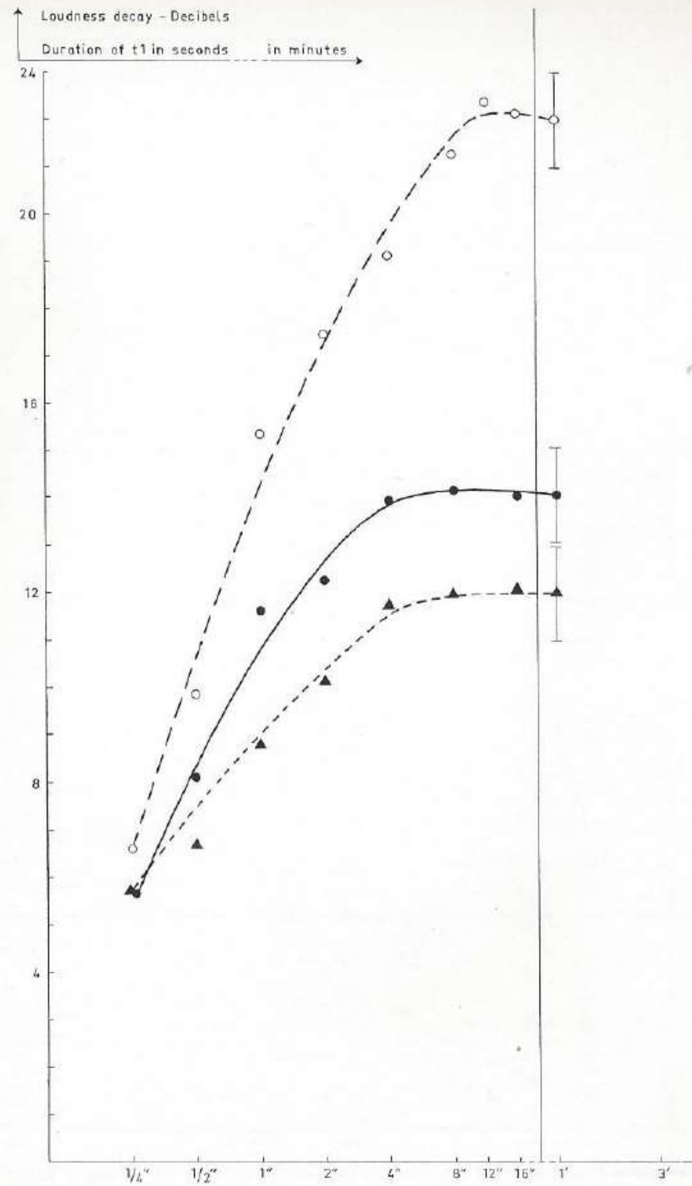



Figure 13 Perstimulatory procedure. Loudness decay as measured at the end of $p_1$. Parameters: intensity of $p_1$.

O– – –O $p_1$ = 73 dB
●——● $p_1$ = 53 dB
▲- - - -▲ $p_1$ = 33 dB

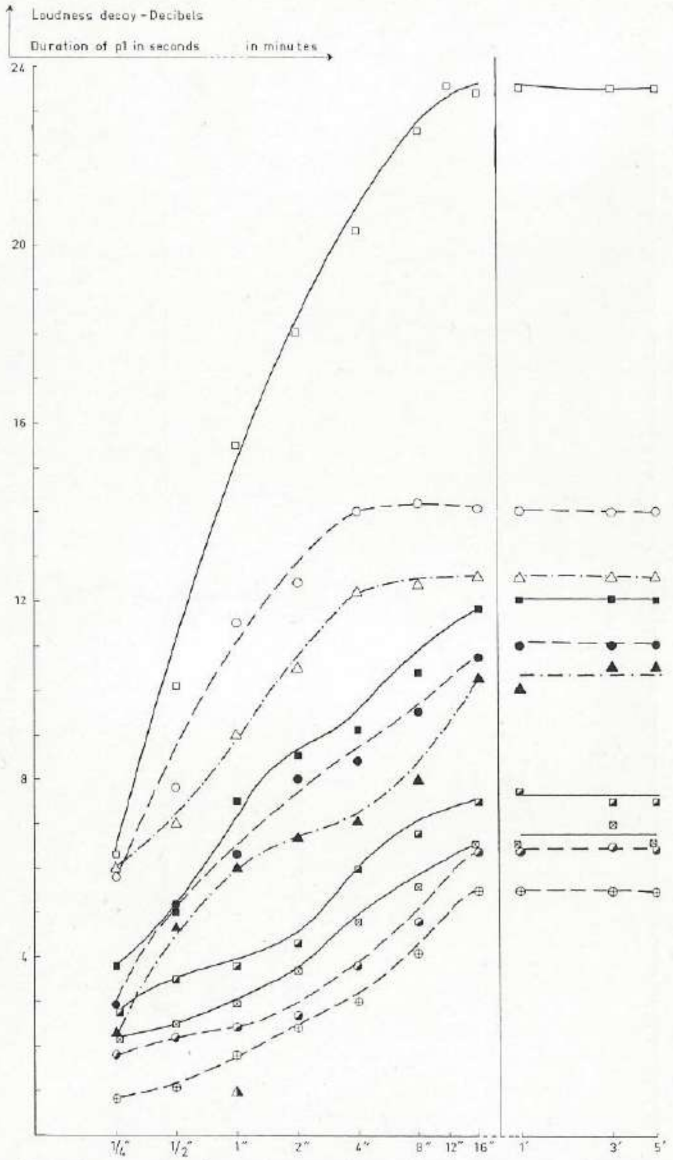



Figure 14 Typical example of a subject, whose observations at different experimental conditions are plotted in one figure. Parameters: intensity of $p_1$ and interstimulus interval.

| | |
|---|---|
| ——— $p_1$ = 73 dB | □ t = 0 msec |
| — — — $p_1$ = 53 dB | ■ t = 20 msec |
| ·—·— $p_1$ = 33 dB | ◪ t = 80 msec |
| | ⊠ t = 160 msec |
| | ▲ $p_1$ = 33 dB, t = 160 msec |



oscilloscope (Tektronix type 564). At the 73 dB intensity we introduced a 12 sec stimulation duration, because we were eager to know where between 8 and 16 seconds the plateau of the maximal loudness decay had been reached (cf. fig. 13).

As can be easily read from the curves of the figure the influence of the intensity of the test stimulus on the measurable loudness decay is very important. The difference with the poststimulatory trials is already present at the 250 msec duration period of $p_1$. It should be emphasized that the maximal loudness decay at the 33 dB intensity level is identical to that reached in the poststimulatory procedure after 20 msec interstimulus interval, although in this experiment it is reached within 4 instead of 16 seconds. The most surprising result of this experiment is the steep curve of the 73 dB condition, which amounts to a factor 2 compared with the slope and maximal value of figure 11. Comparing the results with the 73 dB signals we may state that the return from this functional state of activity is very fast in the first 20 msec pause. As a typical example the results of one subject are plotted in one figure (cf. fig. 14). For the sake of obtaining a clear picture the measurements with an interstimulus interval of 40 msec are excluded, because they resemble very much those of the 20 msec interval.

## V DISCUSSION AND CONCLUSION

In order to obtain more information on the phenomenon of loudness decay during sustained acoustic stimulation, psycho-acoustic experiments were designed as described in the preceding paragraphs. The results obtained with them when applied to normal hearing subjects were described.

If we consider the results of the experiments the first important inference is that, valuable for loudness levels up to 73 dB SPL, no further change is observed in the functional auditory state of the ear after 16 seconds of continuous stimulation. The loudness sensation seems to be fixed then at a constant level independent of the duration of the acoustic stimulus.

### Development of loudness decay as a function of the stimulation period

Derbyshire and Davis, describing their first observation of adaptation in the auditory nerve of the cat in 1935 noted that; "There is no suggestion of any auditory experience that correlates with the particularly rapid and extensive equilibration which occurs in the auditory nerve of the cat at frequencies near 1000 and 2000 cps." In the first 50 msec the amplitude decrease of the nerve response amounts to an equivalent of 8 decibel (Derbyshire and Davis, 1935). According to Rawdon-Smith (1938) the accompanying change in loudness is almost unnoticeable. With respect to Davis' peripheral hypothesis about the equilibration effect, he stated that these small changes in auditory sensitivity are often masked by much larger changes in the central mediation. However, contrary to Davis he already advocated the theory that the frequency of impulses might provide an important explanation of our judgment of loudness, but he considered the effect of increase of the amount of active nerve fibres to be without relation to this frequency factor. In the last decade both neural mechanisms have been united under one heading with respect to the sensation of loudness, and the raise of intensity of the acoustic stimulus is considered to be represented in the central auditory system by an increase of the amount of active nerve fibres rather than of the mean discharge rate. Up to the present time a fundamental change in the theoretical explanation has neither been suggested nor experimentally demonstrated.

It may be of use presently to follow the development of loudness decay outlined as a function of time duration of the acoustic stimulus. The electrophysiological feature of auditory neurons activity and the psychological correlate in the loudness sensation are compared, starting at the moment of introduction of acoustic stimulation into the ear. According to von Békésy, Miskolczy-Fodor and Bentzen the loudness sensation reaches its maximum after about 160—180 msec at moderate loudness levels of the signal, when the decay starts, i.e. can be experienced. After 190 milliseconds the whole nerve response already reaches its final and more or less constant value according to Derbyshire and Davis. As the figures in the different tabels (II, III, IV, V and VI) demonstrate the first stimulation period of 250 msec contains a period of about 60—80 msec only to account for a considerable and quick



decay of loudness. From the same figure we derive a further rather quick decay up to a one second period of stimulation. After that period 0.5 to 0.6 of the total measurable loudness decay expressed in decibels is reached, while within four seconds of continuous stimulation more than 3/4 of its maximum is measured. These factors are rather constant in all experimental conditions. In the next 12 seconds only a few more decibels are added to the decay.

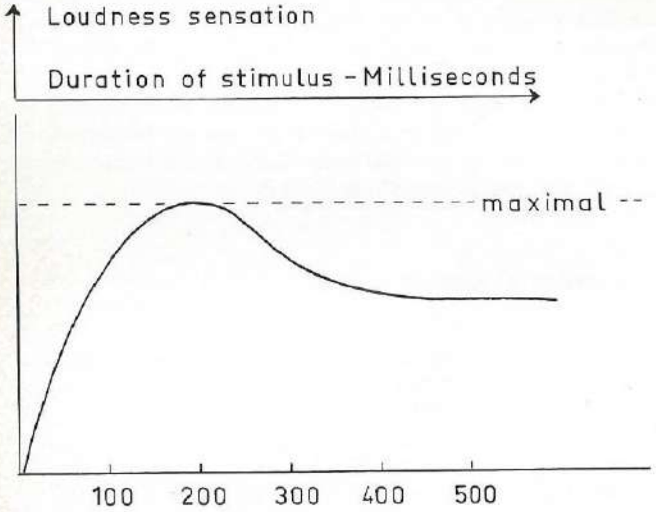



Figure 15a

Represents the hypothetical picture of growth and decay of loudness sensation during sustained acoustic stimulation.

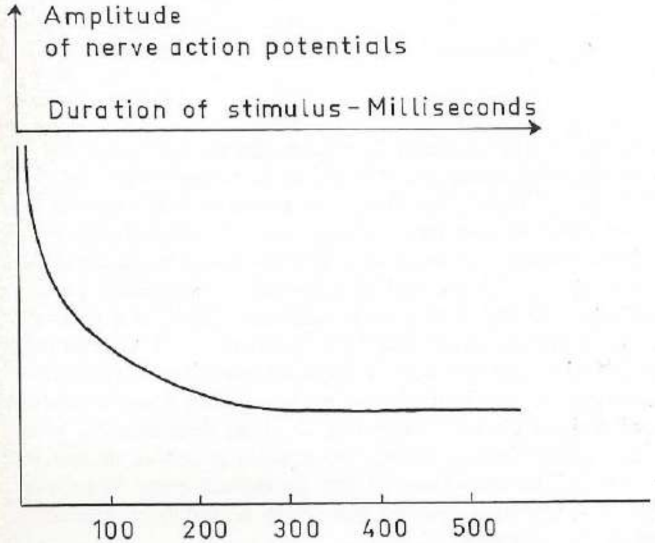



Figure 15b

Represents the fast equilibration of nerve action potentials as found by Derbyshire and Davis.

The schematized picture of growth and decrease of loudness sensation (cf. fig. 15) suggests a rather quick onset of the loudness decay, obviously starting with a sharp bending from the point of maximal loudness sensation and reaching a maximal value asymptotically after another sharp bending of the curve. In the representations of the measured loudness decay we observe the first quick onset by comparing the slope of an extrapolated line back to zero decibel, with the trend of the next part of the curve, which shows a less steep slope. In figure 9 another steep rise of the curve is seen after 1 and 2 sec duration periods of $p_1$ respectively. After 4 and 8 sec the second quick rise tends to reach a definite value, that appears to be constant in periods of several minutes. At a much lesser degree this two-fold quick rise of loudness decay can be seen in figure 10, where it is measured after 80 and 160 msec interval. In contrast to the 40 msec interval condition of measuring the curves of figure 11 show a more constant rise of the decay. However, the two stages of quick rise in the 40, 80 and 160 msec interval condition suggest not a single but a plural neurophysiologic mechanism.

### Loudness decay as a function of intensity of $p_1$

Because of the dependence of the loudness decay on the intensity of $p_1$, we have to range the results of the experiments according to various parametric functions. The results in table II and IV show that the maximal decay, measured both after a 20 and a 40 msec interval is not dependent on the intensities choosen, 53 and 73 dB. Using a tone of 33 dB with an interstimulus interval of 20 msec (cf. table IV) the maximal value differs only one decibel from that of the 73 dB tone. But varying the interstimulus interval to 80 and 160 msec precludes reaching the above mentioned maximum. The 80 and 160 msec interval experiments demonstrate a clear dependence of the loudness decay on the intensity of $p_1$, but differences seem to remain constant in both conditions (cf. fig. 16).

We plotted the difference between 53 and 73 dB results as a function of the stimulation period with the interstimulus intervals as parameters (cf. fig. 17). The bracketing way of the 20 msec line does not seem to indicate any difference, even after five minutes. On the contrary the 40, 80 and 160 msec interval experiments demonstrate a difference, which demands an explanation. The constant difference at one, three and five minutes stimulation periods similarly seems to indicate that the process of loudness decay and recovery proceeds at different rates during 53 dB and 73 dB stimulation. The difference shows a maximum at 2 and 4 sec periods. It appears reasonable to assume that the 73 dB condition does not recover as rapidly in the interval as the 53 dB condition, though values obtained with the 20 msec interstimulus interval do not suggest any other than a strictly reversible process underlying the measured phenomenon. The decrease of the difference after 4 seconds of stimulation indicates that the 53 and even the 33 dB stimulation conditions incur some retardation of the recovery.



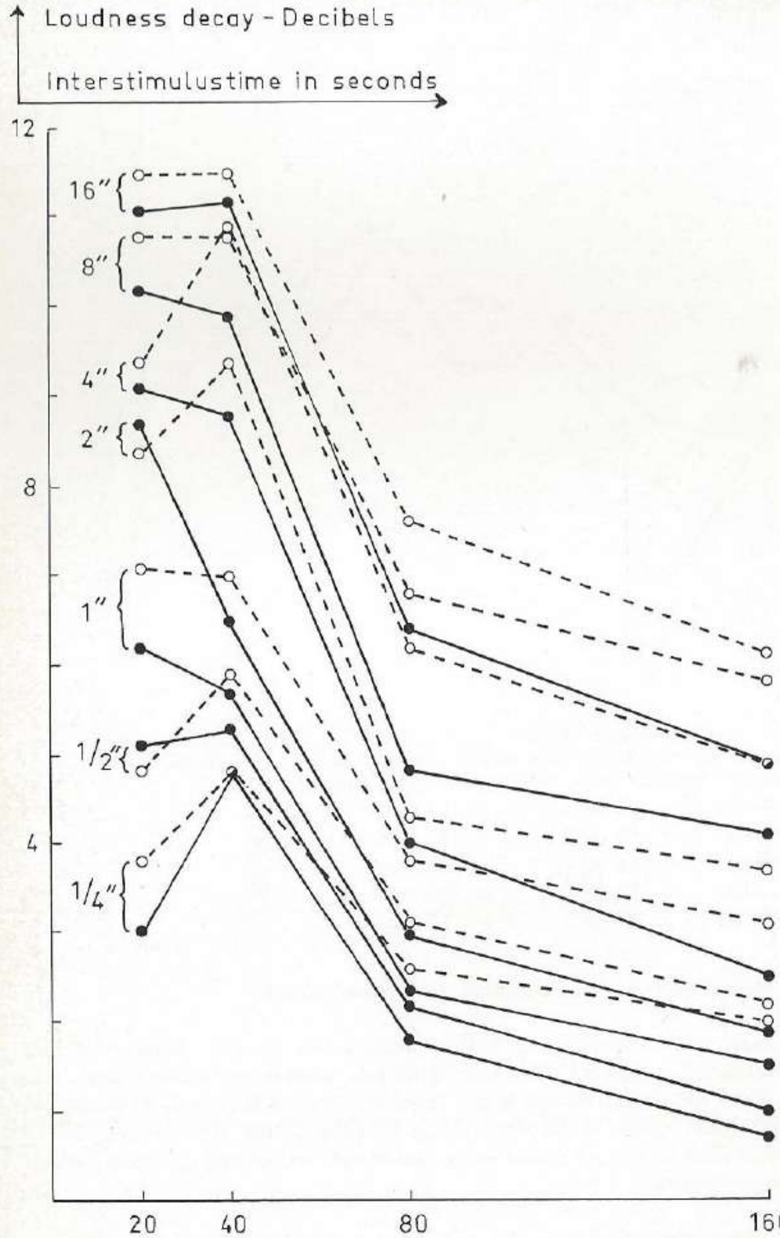



Figure 16 Loudness decay plotted as a function of interstimulus interval. Parameters: Intensity and duration of $p_1$.
O- - - -O 73 dB; ●——● 53 dB.

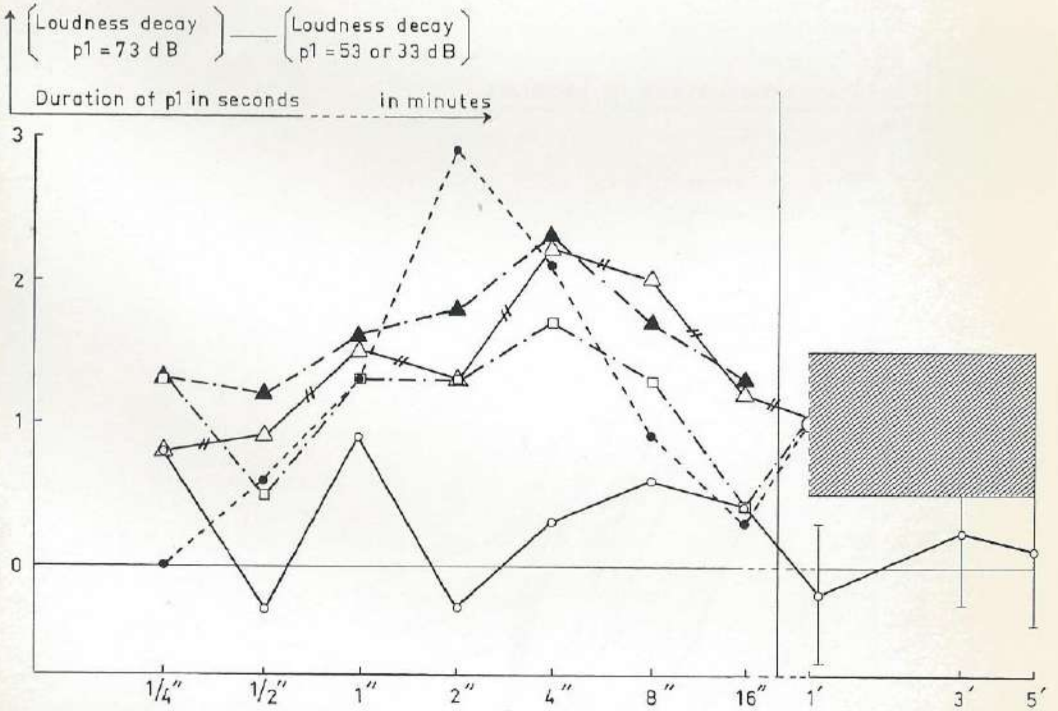



Fig. 17 On the ordinate the difference between 73 dB and 53 dB, and of the difference between 73 dB and 33 dB (one series) results is plotted as a function of duration of $p_1$. Parameters: intensity of $p_1$ and interstimulus interval.

| | | |
|---|---|---|
| O——O | $p_1$ = 53 dB | t = 20 msec |
| ●- - -● | $p_1$ = 53 dB | t = 40 msec |
| Δ-//-Δ | $p_1$ = 53 dB | t = 80 msec |
| ▲-·-▲ | $p_1$ = 53 dB | t = 160 msec |
| □·-·-□ | $p_1$ = 33 dB | t = 20 msec |

**Final considerations, assumptions and conclusions**

We based the technique of our investigations on the dichotic localization method, which assumes that the loudness sensation in both ears must be equal when the sound image in the head originating from a dichotic stimulation with identical tones is localized in a median plane. Concerning the neural representation of the phenomenon of loudness decay two or more possibilities can be considered.

I The lateralization shift of the imaginary plane within the head where pulses from both ears meet is a consequence of time delay or inhibition of one of the two acoustic messages along the central auditory pathways starting with a synchronous stimulation of the nerve endings in both cochleae. In this case



a decrease in the level of nerve response in one ear, whether brought about by "adaptation", the effect of some neural or sensori-neural mechanism, or by a physical decrease in the intensity of the stimulus, will be transformed as a time information message up to higher auditory centers. (Moushegian et al. 1964).

II The lateralization shift of the sound image, when presenting identical stimuli dichotically is determined by the ratio of the extent of active fibre arrays in the central auditory pathways of both sides. (Galambos et al. 1959, Odenthal, 1964).

The second assumption is more attractive than the first one, owing to the suggestion which it induces that the phenomenon of loudness decay takes its origin at a peripheral neural localization, i.e. the starting point of all auditory nerve impulses. This would better fit in with a sensori-neural "feedback" mechanism as a garantee for the most economical state of activity than a central time delay of acoustic messages.

Presently it will have to be endeavoured to base the data of our experimental investigations on some known facts of the electro-physiologic study of the central auditory pathways. Starting at the onset of acoustic stimulation we find evidence where up to some 190 millisecond period the loudness sensation grows to a maximum, its underlying mechanism being not a matter of physical principles, but a neural process of optimal firing rate along the central auditory pathways. From the onset of acoustic stimulation each nerve response decreases to a constant number of discharges per second which process seems to be completed within one second, although only during the first tenth of this second the change is considerable (Davis et al. 1962). Although at some 180—190 milliseconds of stimulation the psycho-acoustic phenomenon seems to coincide with the electro-physiologic events, its development after the first second up to a prolonged stimulation is different from the observed changes in the rate of discharge in nerve responses. However, we may state here that the characteristics of the psycho-acoustic measurements resemble those of the physiological observations of Coats (1964) with respect to the influence of intensity and duration of the signal on the recovery of the auditory sense organ. To what extent the descending auditory system, the oliveo-cochlear tract does interfere with these processes is unknown up to now, although investigations in that matter seem to have procured some information (Fex, 1962). Some facts as the decrease of action potentials (whole nerve response) within 10 or a few more msec suggest the presence of a peripherally localized process unaccompanied by any descending inhibitory nervous mechanism. Another uncertain fact in this respect is the latency of the so called "feedback mechanism by way of the tract of Rasmussen" in which electro-physiologic measurements differ from 11 to 500 msec (Pfalz, Desmedt, Fex, 1962; Rupert, Moushegian and Galambos, 1963).

Assuming that the first rapid decay of loudness is the psycho-acoustic correlate of the already started neural adaptation process "along" the central auditory pathways, the decay being due to a measurable output of this central acoustic nerve system and not an intrinsic phenomenon somewhere up in its course, we can also assume that the second phase of decay can be due to both an efferent mechanism, as suggested by Fex, Desmedt and others, and the final (more or less) peripheral adjustment (Rupert et al., 1963).

The publications of Ingham (1957, 1959), Chocholle (1960), Sherrick and Mangabeira-Albernaz (1961) and recently Dirks and Malmquist (1965) dealing with cross-masking by pure tone or narrow band noise pulses strongly suggest interfering effects of central masking in dichotic stimulation with pure tone or noise pulses. Evidence of the supposed neural interaction unfortunately is hard to derive from the experiments of Hood, Palva, Egan, Jerger and Wright owing to the indetermined functional state of the control ear in their experiments. The original statement of Ingham says that during acoustic stimulation at the contralateral ear a threshold shift of more than 10 dB can be observed with a loudness level of the acoustic stimulus (f testtone = f masking tone) of 30 dB SPL. Sherrick and Mangabeira-Albernaz, who worked with pulsed stimuli, found the largest threshold shift in a dichotic pulsed condition. They reported a threshold shift in the different parametric functions, between 5 and 10 dB. They, however, did not use insert-receivers contrary

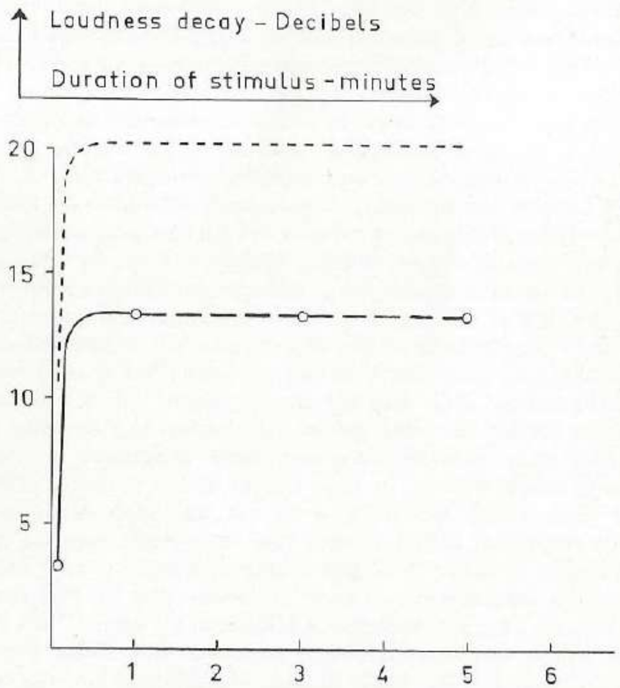



Figure 18 The lower solid curve represents the graphic picture of the loudness decay plotted as a function of duration of the first stimulus (intensity is 53 dB). The interrupted line represents the hypothetical picture of the loudness decay of the same stimulus with a central masking effect taken in account.



to Dirks and Malmquist, who maintained an excellent interaural insulation in their experiments. They also reported results that were in agreement with those of Sherrick and Mangabeira-Albernaz. This effect, already established with loudness levels of 30 and 40 dB, producing threshold shifts of 4 to 5 dB in the contralateral ear, seems to be slightly progressive when the intensity of the masking signal grows, which progression is about one decibel per ten decibel loudness increase of this masking signal.

Returning to the experiments described, we think it reasonable to assume that the effect of contralateral masking can be an important bias in our testing procedure. Considering the fusion of the two curves of 73 dB (cf. fig. 11), which suggests that acoustical leakage between the ears is not of importance, we further assume that a central mechanism does account for the cross-masking. As stated by Moushegian, Rupert and Whitcomb in their elaborate study of medullary auditory responses to binaural tones (1964), there is ample evidence that binaural interaction occurs throughout most of the central auditory system, probably starting at the level of the superior olivary complex. This means that the peripheral neural adaptation processes are limited in their psycho-acoustic representation when both ears are used in a dichotic stimulation procedure. Therefore it appears reasonable that the quantitative aspect of the results of this study will be especially important, if central masking has the effect as supposed (cf. fig. 18).

## SUMMARY

In order to obtain supplementary data on the decay of loudness sensation during sustained acoustic stimulation with pure tones, five subjects were submitted to psycho-acoustic experiments with a binaural lateralization procedure. Loudness decay is defined as the temporary shift in loudness of a sustained acoustic stimulation at moderate loudness levels.

From electro-physiologic experiments it is known that the neural adaptation develops within a few tenths of a second of acoustic stimulation. It was the purpose of this study to investigate the rate of development of the loudness decay from the onset of sustained stimulation on, and to compare this development as a function of time duration of the stimulus with the same relation in the electro-physiologic experiment.

Contrary to the conventional theory of the growth of loudness decay mentioned as auditory loudness adaptation in the literature, evidence has been drawn from this study that the loudness sensation shows a very fast decay during the first 250 msec of stimulation and that within 4 seconds more than 75% of the measurable amount of decay is reached.

These experimental findings indicate that loudness decay as a function of time duration of the sustained stimulation is associated with the neural adaptation process. According to the testing procedure, the intensity of the acoustic stimulus up to 73 dB SPL, appears to be a quantitative factor with

respect to the measurable loudness decay. However, when the experimental results are biased by effects of central masking, the intensity as such might be of still more quantitative influence than this study suggest.


**RÉSUMÉ**

Des expériences psychoacoustiques ont été effectuées pour étudier d'une façon plus approfondie l'adaptation auditive consécutive à une stimulation continue provoquée par un ton pur. La méthode employée est un procédé de latéralisation d'une image sonore par une stimulation acoustique binaurale.

On entendra par adaptation auditive ou diminution de la sensation d'un ton continu, la diminution temporaire de la sensation sonore provoquée par une stimulation tonale continue d'une intensité modérée.

Par des recherches électro-physiologiques on sait déja depuis longtemps que la décroissance de l'activité électrique de la voie acoustique s'accomplit pendant deux cents millisecondes de stimulation continue. Le but de cette étude a été de préciser la vitesse de la diminution de la sensation sonore et de montrer sa corrélation avec le phénomène électro-physiologique.

Contrairement aux théories établies sur le développement de l'adaptation auditive cette étude montre que l'adaptation auditive se développe avec une grande vitesse pendant le premier quart de seconde après le commencement de la stimulation par un ton pur continu, à tel point qu'il existe une diminution de plus de 75% des le premier quart de seconde.

Ces épreuves expérimentales indiquent que l'adaptation auditive, mesurée comme fonction du temps de la stimulation tonale, semble être liée au phénomène électro-physiologique. La méthode pratiquée dans cette étude montre que l'intensité du ton continu est d'une grande importance dans la diminution de la sensation sonore.

Cependant, si l'on considère que les résultats de toutes ces expériences ont été affectés par l'effet inhibitoire résultant de l'interférence entre les voies auditives droite et gauche, il est possible que l'influence de l'intensité du ton continu soit encore plus importante que les résultats de cette étude semblent le suggérer.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# STELLINGEN

I

De opvatting van Ranson dat vezels der fasciculus posterolateralis van Lissauer een exclusieve schakel in de pijngeleiding vormen is op morphologische gronden aanvechtbaar.

(J. Szentagothai: J. Comp. Neurol., 122; 219—240, 1964)

II

Woordblindheid moet beschouwd worden als een stoornis in de informatie-verwerking. Oogheelkundige afwijkingen kunnen daarbij desnoods een tweede handicap vormen.

III

De Békésy-audiometrie dient als het belangrijkste diagnostische hulpmiddel toegepast te worden bij het onderzoek van doofheden van onbekende cochleaire of retro-cochleaire aard.

IV

Doordat in de door Stuiver en Köster ontwikkelde geurstimulator de geurkanalen niet volledig gescheiden zijn is dit apparaat voor het onderzoek van de geurperceptie slechts van beperkte betekenis.

V

Efficiënt foniatrisch onderwijs is zonder voorafgaand stem-analytisch onderzoek niet doeltreffend.

VI

Het nut van het decomprimeren van de nervus facialis bij de Bell'se paralyse moet nog bewezen worden.

VII

Het adagium «l'Alpinisme n'est pas la guerre» is vooral tekenend voor de Franse mentaliteit in deze moeilijke sport.

B. A. WITTICH

LEIDEN