Psychophysical Comparison of the Auditory and Vibrotactile Perception-Absolute Sensitivity

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In this paper, the psychophysical abilities and limitations of the auditory and vibrotactile modality will be discussed. A direct comparison reveals similarities and differences. The knowledge of those is important for the design of audio-haptic systems, multimodal music applications or perceptually optimized human-machine interfaces. Literature data and own results for psychophysical characteristics are discussed. This paper focuses on the absolute perception thresholds of both modalities. The main factors which influence these thresholds are discussed: age, energy integration, masking and adaptation.

INTRODUCTION

The perception of vibrations at the skin and sound are often coupled in real life, e.g., while playing an instrument or listening to music with low frequency content. In these cases, the physical stimuli which excite both modalities are usually highly correlated. If new multimodal systems are designed, sound and vibrations can be influenced separately. Just think of the auditory and vibrotactile feedback of a button on a touch screen, or vibrotactile feedback of electronic music instruments, or bimodal devices for guidance of blind persons. For example, the authors developed and optimized systems for multimodal reproduction of music. To this end, a vibration actuator was coupled to a surface in contact with the listener, e.g., an electrodynamic shaker mounted in a backpack, integrated in clothing or attached below a seat or floor. Audio reproduction was implemented with conventional loudspeakers or headphones. To generate appropriate music-related vibrations from the audio signal various signal processing approaches were compared. It was found that it is beneficial to consider the perceptual capabilities and limitations of both modalities in this design process. Therefore, knowledge of the fundamental characteristics of the auditory and vibrotactile sensory modalities was necessary. Many similarities can be found regarding psychophysical characteristics, although the anatomy and physiology of both modalities is quite different. A good overview of the basic structure and functionality of the human hearing organ as well as the histology and physiology of the mechanoreceptive system including the neural processing in the somatosensory and auditory areas of the brain can be found in [45] and will not be described here.

The current survey aims to compare the sense of hearing and touch using data from psychophysical experiments. Special attention is given to the perception of vibrations in the frequency range where sound and vibration perception overlap: between a few Hertz and several hundred Hertz. The authors hope that this overview helps to design good auditory-tactile feedback that matches perceptually. Because of limited space, this paper focuses on absolute perception thresholds. The main factors which influence these thresholds are discussed: age, energy integration, masking and adaptation. This paper is based on the dissertation of the first author [36]. Reproduction is kindly permitted by the Shaker Verlag, Germany.

The perception of sound has been studied for several decades. The basic physical attributes of sound (e.g., intensity, frequency or location of a sound source) have been correlated to perceptual attributes like loudness, pitch or distance. Different effects like adaptation to loud signals or masking characterize the auditory system. In contrast to our hearing, vibrations can be perceived at different parts of the body. Most vibrotactile studies focus on vibrations transmitted via hand and finger. However, the principal mechanoreceptors in the skin are similar at different body sites. In the overlapping frequency range of auditory and vibrotactile perception, vibrations are likely to stimulate mainly the Meissner and Pacinian mechanoreceptors which can be found all over the body [45], however, with varying populations and surrounding tissue mechanics. Nevertheless, data from different body sites is used for a general comparison.

A common measurement unit for sound is the sound pressure level. L_{SPL}. It is defined as the logarithmic ratio of the effective value of the sound pressure p and a reference value $p_0 = 20\,\mu\mathrm{Pa}$:

$$L_{\mathrm{SPL}} = 20 \log \frac{p}{p_0} \mathrm{dB}.$$

A similar unit for measuring vibrations is the acceleration level L_{acc}. It is defined as the logarithmic ratio of the acceleration a and a reference value $a_0 = 1\,\mu\mathrm{m/s}^2$:

$$L_{\mathrm{acc}} = 20 \log \frac{a}{a_0} \mathrm{dB}.$$

In contrast to sound pressure level, 0 dB acceleration level is not related to the perception threshold. Therefore, sensation level (the level above threshold) will be used to compare the auditory and vibrotactile modality directly. Please note that within this paper the term 'vibrotactile' will be sometimes abbreviated as 'tactile'. However, the article will not discuss other types of tactile sensations (e.g., temperature).

SENSATION AREA

A fundamental characteristic of a sensory modality is the absolute perception threshold. Minimum and maximum perceivable levels for auditory and vibrotactile perception will be discussed in this section.

AUDITORY

Sound can be heard between approximately 20 Hertz and 20 kHz. Below 20 Hz the tonal sensation ceases, and below 10 Hz single cycles of the sound can be perceived [41]. The upper frequency limit depends strongly on the age of the subject. Figure 1 shows that the hearing is most sensitive to sound pressure between approximately 300 Hz and 7000 Hz.

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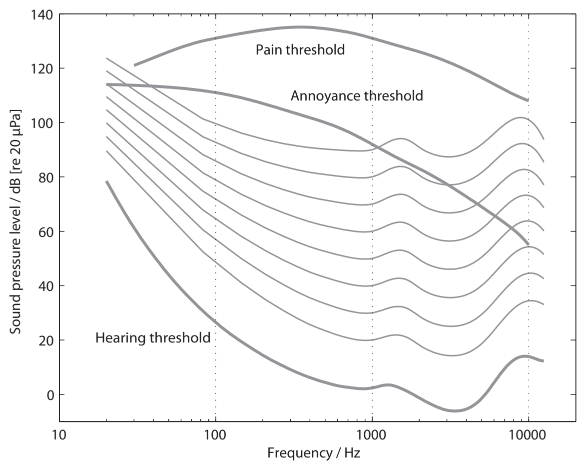

Figure 1: Curves of equal subjective intensity plotted as a function of frequency for sounds (according to ISO 226:2003 [29] and Winckel [64]).

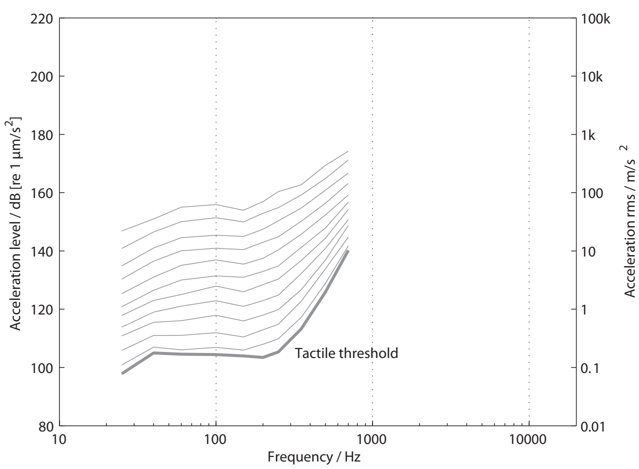

Figure 2: Curves of equal subjective intensity plotted as a function of frequency for vibrations of a 2.9 cm^2 contactor on the thenar eminence (adapted from Verrillo [59]).

It becomes less sensitive for decreasing and increasing frequency. In addition, the figure shows estimates for the pain threshold and the annoyance threshold after Winckel [64]. The curves of equal subjective intensity (equal loudness contours) are plotted according to ISO 226:2003 [29]. They follow the threshold curve to some degree. It can be seen that they get closer toward lower frequencies. The auditory dynamic range is thus frequency dependent from 50 dB to more than 100 dB.

The hair cells in the cochlea can be regarded as the most sensitive mechanoreceptors of the human body. The minimum perceivable sound pressure causes only 10^{-10} m displacement in the inner ear, which corresponds roughly to the diameter of a hydrogen atom [45].

Tactile

In comparison the vibrotactile sense is rather limited. Only frequencies up to approximately 1 kHz can be perceived via the mechanoreceptive system. Similar to the ear, the vibration sensitivity of the skin depends on frequency. Figure 2 shows the frequency dependent perception threshold on the thenar eminence adapted from Verrillo et al. [59]. It can be seen that the glabrous skin becomes more sensitive to the acceleration of its surface with decreasing frequency. Similar results were reported for various regions of the body [24]. It was found that the sensitivity depends on the distribution and density of the mechanoreceptors, with lower thresholds for areas with higher receptor density [31]. Hairy skin is approximately 10 dB to 20 dB less sensitive depending on frequency [57].

The curves of equal subjective intensity follow the threshold to some degree. Again a frequency dependence can be seen, with smaller dynamic ranges for frequencies above approximately 300 Hz. At frequencies below 200 Hz, vibrations more than 40 dB to 55 dB above threshold become very unpleasant or painful [40]. The dynamic range can thus be quantified between approximately 40 dB to 50 dB.

Similar curves of equal vibration intensity have been measured by the authors for seat vibrations using two different methods: magnitude estimation and intensity matching. Interestingly, the slight frequency dependence of the dynamic range could not be confirmed [37].

The growth of perceived intensity above threshold is another very important aspect when comparing the auditory and vibrotactile modality.Compared to audition, the increase in perceived magnitude is steeper with increasing level in the vibrotactile domain, particularly at low sensation levels.For a detailed discussion of this relevant topic, it is referred to [36] where a new perceptually motivated measurement was proposed to represent human vibration intensity perception: the perceived vibration magnitude M in vip, comparable to auditory loudness N in sone.

Age and Gender

Auditory

The threshold of hearing rises naturally with increasing age. This effect is referred to as presbyacusis and involves primarily frequencies above 3000 Hz. Figure 3 presents data that depicts the progression of hearing loss with age [46]. The data is averaged over men and woman, however, it has been shown that presbyacusis starts more gradual in women but grows faster once started [3]. In addition, noise-induced hearing loss (sociocusis) is a common phenomenon today.

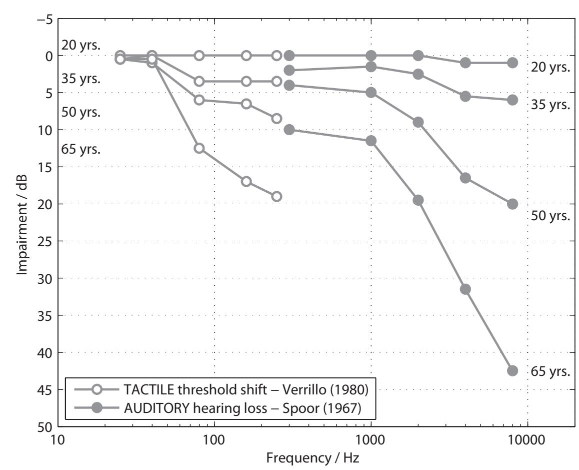

Figure 3: Auditory and vibrotactile threshold shift as a function of age. Auditory data depicts presbycusis (without the effects of severe occupational noise) [46]. Vibrotactile data are achieved using a 2.9 cm² contactor at the thenar eminence [56] and plotted relative to the threshold at 20 years. The data points at 250 Hz are shifted slightly for better illustration.

TACTILE

Similar to hearing, age has a considerable influence on vibrotactile thresholds. The sensitivity for high frequencies decreases progressively with age [48, 58]. Figure 3 illustrates the shift of the vibrotactile detection threshold for four age groups [54]. At higher frequencies, where the Pacinian system is predominant, a strong loss of sensitivity can be observed with increasing age. No effect was found for low frequencies.

In general, no gender differences were found for vibrotactile thresholds between men and women [55, 35]. Only Gescheider reported that woman are slightly more sensitive to high-frequency vibrations at the thenar eminence a few days before menstruation [20].

ENERGY INTEGRATION

An other important characteristic of the auditory and vibrotactile modality, which has an influence on the threshold, is the ability to integrate energy. This is often discussed using the relationship between the duration and the threshold (or intensity) of a stimulus.

AUDITORY

The auditory threshold of detection decreases with increasing duration up to a stimulus length of approximately 1 s. This holds true for various types of stimuli over a broad frequency range [13]. Figure 4 shows data from Plomp and Bouman [44] and Florentine [12] for a stimulus frequency of 250 Hz. The curves follow the prediction made by the theory of temporal summation, which was formulated by Zwislocki in 1960 [65].

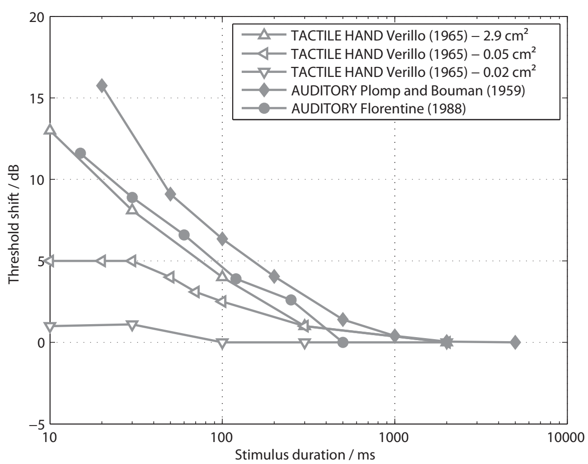

Figure 4: Auditory and vibrotactile threshold shift as a function of burst duration after [44, 12, 51]. Data are plotted in dB re threshold of detection for the longest stimulus of each curve. In all cases, the stimuli frequency was 250 Hz. The vibrotactile stimuli were applied to the skin of the hand using different contactor sizes.

TACTILE

Temporal energy integration can also be found in the vibrotactile domain, but only in the Pacinian system [15, 16]. No temporal summation was found for low frequencies, e.g. at 25 Hz [18]. Data after Verrillo [51] are plotted for comparison in Figure 4. Stimuli with a frequency of 250 Hz were delivered to the glabrous skin of the palm using a large contactor (2.9 cm^2). He measured a 3 dB reduction of threshold per doubling of duration up to a stimulus length of 300 ms, indicating a complete integration of energy. Similar curves were found at 100 Hz and 500 Hz, frequencies at which mainly the Pacinian corpuscles are responsive to vibration. The same trend was found in suprathreshold experiments [1]. Other experiments by the author with seat vibrations at 40 Hz, 80 Hz, 160 Hz and 320 Hz confirmed the above conclusions but are not plotted here for clarity [38]. The data agrees well with the curves found in the auditory domain in spite of fundamentally different biomechanical conditions of the tactile sense compared to hearing. It remains open if this suggests similar perceptual mechanisms or if it can be explained otherwise, e.g., by surrounding tissue mechanics.

Additional curves for smaller contactor sizes (0.05 cm^2 and 0.02 cm^2) can be seen in Figure 4 [51]. As the size of the stimulated area is reduced, the dependence of duration upon the threshold is accordingly reduced. Using smaller contact areas, more and more non-Pacinian receptors will be stimulated [45]. Consequently, the amount of temporal summation declines.

In addition, absolute vibrotactile sensitivity at higher frequencies depends strongly on the size of the stimulated area. It has been shown that for frequencies between 80 Hz and 320 Hz (Pacinian channel) the threshold decreases with 3 dB per doubling of contact area at the thenar eminance of the hand [52, 50]. Similar results have been reported for the hairy skin at the forearm [53]. No effects were found for lower frequencies [18].

Until now, only a single stimuli has been examined. However, in everyday life, two or more simultaneous stimuli are not unusual. If subjects are asked to judge the combined intensity of two tones, the result is proportional to the overall energy if the frequencies lie within a critical band in audition. However, if frequency components outside the critical bandwidth are added, the perceived intensity grows much stronger and the sensation magnitudes of the individual components can be summed [11]. Interestingly, similar effects have been found in the vibrotactile domain. Evidence for energy integration within the Pacinian channel has been discussed above and addition of sensation magnitudes between mechano-receptive channels has been reported [60, 34]. It was therefore suggested that the Pacinian channel is analogous to a critical band in the auditory system [32].

MASKING

If multiple stimuli are heard or felt in close temporal proximity, they might interfere. One such effect is the suppression of one stimulus by another, which is called masking.

AUDITORY

Early experiments used two sinusoids as masker and test signal to investigate masking ([63] as cited by [42]). However, when both signals were close together in frequency, beats occurred and complicated the results. To avoid this problem, later studies used narrow band noise as masker. The shifted threshold for detecting a test tone at various frequencies in the presence of a masker with fixed center frequency and amplitude was determined. This masked threshold is sometimes called masked audiogram or masking pattern. It is strongly correlated with the excitation pattern the masker generates on the basilar membrane [4]. An exemplary masking pattern is shown in Figure 5 with data from [6]. For the plotted curve, a 90 Hz wide band of masking noise is centered at 410 Hz with 40 dB SPL. A narrow masking region can be seen. However, for higher sensation levels, which are not plotted here, the masking pattern spreads especially towards the high-frequency side.

In general, auditory masking pattern are dependent on masker frequency, duration and level. They show steep slopes towards lower frequencies and less steep slopes towards higher frequencies on a logarithmic frequency axis. However, towards low sensation levels or low frequencies, masking patterns are getting more and more symmetrical [6, 49], as illustrated in Figure 5. Interestingly, low frequency maskers

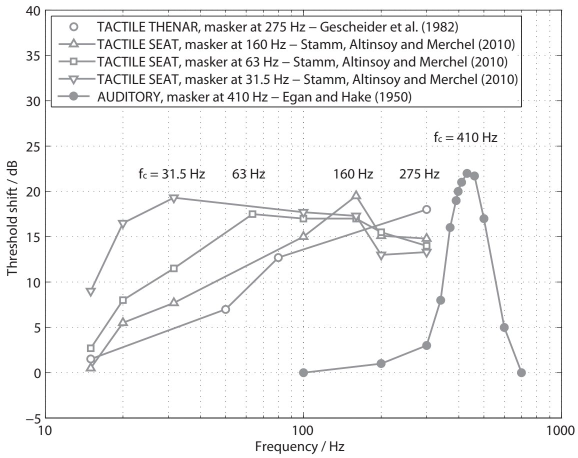

Figure 5: Auditory and vibrotactile masked thresholds relative to unmasked condition as a function of frequency. The vibration masker were narrow band noises centered at 31.5 Hz, 63 Hz, 160 Hz and 275 Hz with fixed level approximately 25 dB above threshold. Data from Stamm, Altinsoy and Merchel [47] are plotted for whole-body vibrations (25 Hz noise bandwidth) and from Gescheider et al. [21] for vibrations at the thenar eminence (100 Hz noise bandwidth) . For comparison, an auditory masking pattern is plotted for a 90 Hz wide band of masking noise, centered at 410 Hz with 40 dB SPL [6]. Test stimuli were simultaneously presented sinusoids in all conditions.

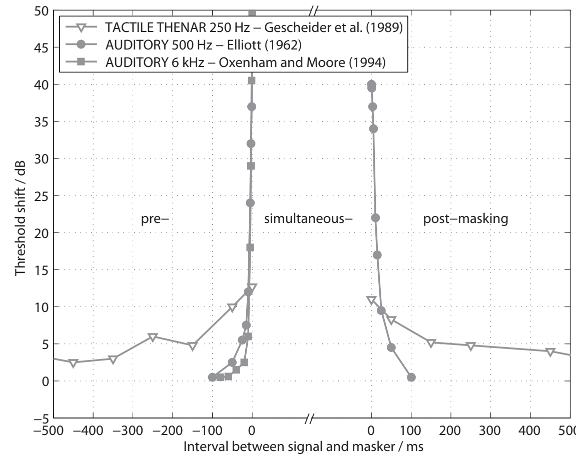

Figure 6: Auditory and vibrotactile pre- and post-masking as a function of the gap between signal and masker. Data from Gescheider et al. [17] is plotted using a 250 Hz vibration masker at the thenar eminence with 20 dB sensation level. The test signal was also a 250 Hz vibration. For comparison, auditory data from Elliott [9] is plotted using a white noise masker at 90 dB SPL. The test signal was a tone at 500 Hz. Additionally, pre-masking is plotted after Oxenham and Moore [43] using a noise masker and a 6 kHz tone.

(e.g. at 150 Hz) seem to have their maximum effect slightly shifted towards higher frequencies [49] and their masking pattern broadens significantly [7, 8].

In the above studies, masker and test signal have been presented to the same ear or both ears diotically. However, even for dichotic conditions masking was found [9, 10]. Therefore, central processing must be involved in the masking process, since the masker is presented to one ear and the test signal to the other.

Even if the masker and the test signal are presented one after the other, masking effects have been reported. This is referred to as post-masking (forward masking) if the test signal comes slightly behind the masker, or pre-masking (backward masking) if the test signal precedes the masker as is illustrated in Figure 6 using data from Elliott [9]. A 50 ms long white noise masker at 90 dB SPL was used to mask a 7 ms long test tone at 500 Hz. It can be seen that post-masking is active up to approximately 100 ms. Other studies reported slightly longer post-masking intervals, e.g. Jesteadt et al. [30] used tones from 125 Hz to 4000 Hz and reported that more post-masking occurred at very low frequencies than at high frequencies. Pre-masking is believed to be much weaker. Some studies even showed, that pre-masking diminishes or almost disappears if subjects are highly trained [43].

Tactile

Similar to audition, the detectability of a vibration might be reduced by another one. Again, this effect depends on frequency, intensity and timing of both stimuli. As in audition, masking increases as a function of increasing masker intensity and decreasing frequency separation. However, there is good evidence that the different mechano-receptive channels do not mask each other [21, 32]. Vibrotactile masking patterns from Stamm et al. [47] and Gescheider et al. [21] are plotted in Figure 5. Narrow band masking noise was simultaneously presented with sinusoidal test stimuli. Strong masking towards higher frequencies can be seen, which might be due to masking within the Pacinian channel. For decreasing frequencies lower than the masker, the threshold of the Pacinian channel might exceed the threshold of another tactile channel, e.g. RA1, which takes over and gradually reduces the masking effect [17]. In this sense, the overlapping vibrotactile channels could be regarded similar to overlapping auditory bands, however, with only few fixed filters. This would explain the strong asymmetry of vibrotactile masking patterns plotted here.

Thresholds might be elevated, even if two vibrations stimulate the body at different locations [23, 19]. This is referred to as ‘lateral masking’ or ‘supression’ and can be compared to dichotic masking discussed above. In both modalities neuronal and central processes seem to be involved in masking. However, the underlying mechanisms are not yet completely understood.

Similar to audition, masking is strongest for simultaneous stimulus presentation and decreases with increasing interval between test signal and masker [23, 33]. This is illustrated in Figure 6. Vibrotactile masking at the thenar eminence is plotted with data from Gescheider et al. [17] for a sinusoidal masker and test signal at 250 Hz. He found that the rate of decay of post-masking appears to be approximately the same than pre-masking, independent of masker type (sinusoidal or noise) and stimulated mechano-receptor. Compared to audition, temporal masking seems to be much more extended for vibrations at the skin. In addition, for hearing there is a stronger asymmetry towards post-masting.

If more than one stimuli is presented, also other changes in sensation have been reported. E.g., a stimuli can cause a subsequent one to appear more intense, with increasing intensity for decreasing time interval in-between the both. This is called *enhancement* and has been reported for short tone bursts in audition [66] and vibrotactile perception [60].

Adaptation and Fatigue

In the previous section, masking, the ability of an intense stimulus to obscure a second weaker test stimulus, was described. In this section, the ability of a temporally extended stimulus will be discussed to gradually desensitize a sensory channel. This might result in the decline of apparent magnitude of a stimulus during presentation. Even some time after the stimulus has stopped, it might be harder to detect a test signal.

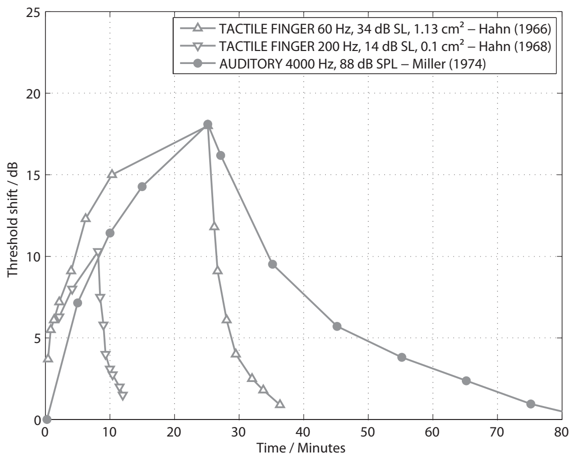

Figure 7: Auditory and vibrotactile temporary threshold shifts during and after exposure to long-lasting stimulation. Data from Hahn [25, 26] is plotted for vibratory stimulation of the Pacinian channel with different intensities and durations. For comparison, an exemplary temporary threshold shift for the auditory system is plotted after Miller [39].

Auditory

In audition it is often distinguished between *adaptation* and *fatigue*. Auditory adaptation refers to the decline in sensitivity within the first minutes of stimulus presentation [42]. However, this effect seems to be restricted to low sensation levels or high frequencies [27, 61]. Auditory fatigue is often understood as the shift in threshold after excessive exposure to a fatiguing stimulus. This temporary threshold shift (TTS) is well known from rock music [5] and will be summarized in the following. The TTS generally increases with increasing intensity and duration of the fatiguing stimulus. Similar to masking, larger TTS have been found with decreasing frequency separation. Interestingly, fatigue effects are less marked at low frequencies, possibly due to the middle ear reflex [42]. After cessation of the fatiguing stimulus, hearing recovers from the TTS approximately proportional to the logarithm of the recovery time, if the TTS is not too large (e.g., < 40 dB) and exposure time is not too long (e.g., < 1 days) [39]. Such an exemplary TTS curve is plotted in Figure 7 for 25 minutes of stimulation at 4 kHz, a frequency where auditory fatigue is most effective.

Tactile

Similar to audition, the absolute perception threshold for vibration increases and recovers over time due to prolonged stimulation. In vibrotactile literature, this effect is sometimes referred to as fatigue and sometimes as adaptation. The TTS increases again with increasing intensity and duration of stimulation. For intense stimulation over a longer period, recovery time can last up to several minutes. Compared to audition, generally much lower sensation levels are required for the effect to appear and much steeper slopes have been reported [2, 62, 22, 14].

Two exemplary TTS curves are plotted in Figure 7 using data from Hahn [25, 26]. The upper curve was measured using a large contact area on the fingerpad vibrating with 60 Hz. Only 34 dB sensation level were necessary to reach 17 dB TTS after 25 minutes of exposure. However, the TTS recovered much faster compared to audition. The lower curve was measured using a small contact area on the fingerpad vibrating at 200 Hz at only 14 dB sensation level. Again steep rising and falling slopes can be seen. Like for masking, it is widely believed, that adaptation can not occur between different vibrotactile channels [26, 28].

Summary

Both modalities show *frequency dependent perception thresholds*, but with different characteristics. When designing auditory-tactile feedback with the goal of equal intensity in both modalities, this disparity can be compensated by careful frequency equalization using the differences between the threshold curves. Compared to the sense of hearing, vibrotactile perception is restricted to low frequencies. At 20 Hz the usable amplitude range of both modalities is similar. However, with increasing frequency the auditory dynamic range increases rapidly, while the vibrotactile dynamic range seems to remain constant up to approximately 200 Hz. Compared to audition, the increase in perceived magnitude is steeper with increasing level in the vibrotactile domain, particularly at low sensation levels. If the target of a multimodal design is to match the perceived intensity of a stimuli in both modalities, the dynamic range of one domain should be adapted, e.g., using a compressor for vibration processing.

Both modalities show severe *impairment of sensitivity with increasing age*. This effect has a similar tendency: it is stronger towards the upper frequency limit of each modality. However, around 250 Hz the age-induced threshold shift seems to be stronger for the sense of touch than for hearing. This is especially crucial in the context of auditory-tactile feedback design, since the vibrotactile dynamic range is considerably smaller than the auditory dynamic range. A vibrotactile threshold shift of 20 dB at 200 Hz almost halves the available amplitude range. In other words: vibrations which are strong for younger subjects, might not be perceived at all by the elderly. Again, dynamic compression in the tactile domain helps the designer to reduce this effect with the drawback of a decreased dynamic range. Because less impairment was reported in the vibrotactile domain below 40 Hz, it might be worth to consider this frequency range for a feedback design which is less dependent on age.

The auditory system is able to *integrate energy* over time for stimuli durations up to approximately 1 s. A similar temporal effect can be found in the vibrotactile system for sufficiently high frequencies and relatively large stimulation areas. In addition energy integration over space has been observed. From this it follows that the size of a vibrating contact area must be taken into account by the designer if the perceived intensities are to be matched in both modalities.

Both modalities show the ability of one stimulus to *mask* (or enhance) an other. In comparison, in the vibrotactile modality broader masking patterns are excited around the masker frequency with strong masking towards higher frequencies. Also in time domain, the vibrotactile threshold is raised over a longer period around the duration of a masker. Strong masking in the vibrotactile modality suggests, e.g., that for a practical auditory-tactile design it might suffice to reproduce the fundamental of a complex sound in the vibratory domain without changing the overall percept.

Temporary threshold shifts due to prolonged stimulation occur in both modalities. In audition high levels or long exposure times are necessary. In the vibrotactile domain, even small sensation levels result in a temporary threshold shifts, which, however, grows and recovers fast. This effect might be relevant for the designer in practical applications if strong background vibrations are present, e.g., when driving a car.

This paper focused on the independent absolute sensitivitiy of both modalities. However, also multimodal effects exist, e.g., the auditory-tactile loudness illusion [36]. In addition to absolute sensitivity, suprathreshold differential sensitivity can be discussed for a psychophysical comparison between the auditory and vibrotactile modalities. However, this gives enough material for another paper.

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