Loudness adaptation with modulated stimuli

Maaïke Van Eeckhoutte, Jan Wouters, Tom Francart

KU Leuven – University of Leuven, Department of Neurosciences, ExpORL,
Leuven, Belgium

INTRODUCTION

The loudness of an auditory stimulus, defined as its perceptual strength [1], can change over time even though the physical intensity of the stimulus remains constant, leading to loudness adaptation or enhancement. Simple loudness adaptation is described as a decrease in loudness judgment of a steady auditory stimulus presented monaurally (for a review see [2]). The term simple is used to distinguish from induced loudness adaptation in which loudness adaptation to a steady stimulus occurs in the presence of an intermittent stimulus in the contralateral or ipsilateral ear [2]–[5]. This study only deals with simple loudness adaptation. In many studies simple loudness adaptation was only found for specific stimulus parameters, such as low sensation levels (<40 dB SL), high frequencies (≥ 2000 Hz), and narrow bandwidths (e.g., pure tones compared to broadband noise). Loudness enhancement, an increase in loudness judgment over time, has been shown to occur for stimuli at high sensation levels [6].

Stimuli that give rise to loudness adaptation are often similar to those commonly used for evoking auditory steady-state responses (ASSRs). These responses are auditory evoked potentials whose frequency components remain constant in amplitude and phase over time [7]. ASSRs are often used in research, and clinically they are used for frequency-specific objective hearing assessments. Typical stimuli for evoking frequency-specific ASSRs are modulated pure tones with carrier frequencies corresponding to the audiometric frequencies of 500, 1000, 2000, and 4000 Hz. While a modulation frequency of 80-90 Hz is mostly used in clinical devices, the largest response amplitudes are evoked with a modulation frequency of 40 Hz and a carrier frequency of 500 Hz [8]–[10]. Amplitude modulation is often used, as well as mixed modulation, a combination of frequency and amplitude modulation. An advantage of mixed-modulation is

that the responses are significantly larger than with uniquely frequency- or amplitude-modulated stimuli [8], [11].

It is currently unclear whether the stimuli used for ASSR measurements *also* cause loudness adaptation. If this is the case, the ASSR amplitude may decrease as well, which might in turn have an impact on the use of ASSRs in clinical practice.

Most simple loudness adaptation experiments have been conducted with pure tones as stimuli. Only Scharf [2], and recently also Wynne [12], investigated more complex stimuli, containing either frequency or amplitude modulation. Scharf did not find any difference in loudness adaptation between pure tones and 50-Hz frequency-modulated tones, which were sinusoidally modulated between 3900 Hz and 4084 Hz at 10 dB SL. In contrast, loudness adaptation with amplitude-modulated stimuli (two-tone complexes) was reduced if the changes in excitation level in the cochlea, produced by amplitude modulations, occurred only within an auditory filter band. Regardless of the modulation frequency, reduced loudness adaptation was also found in Wynne et al. [12] with amplitude-modulated stimuli having a carrier frequency of 12 kHz presented at 15 dB SL.

The purpose of this study was to investigate whether sustained, amplitude- and mixed-modulated stimuli, typically used for evoking ASSRs, cause a change in loudness judgment over time. Carrier frequencies of 500 Hz and 2000 Hz were chosen to compare low and high frequencies. Furthermore, to investigate possible loudness adaptation as well as enhancement effects, a low sensation level of 30 dB SL was compared to a high sensation level of 70 dB SL. An additional aim of this study was to investigate whether the participants' detection thresholds would have an influence on their loudness adaptation behavior.

Stimulus parameters in this study were chosen to enable their use in future experiments involving ASSRs. The different modulation types were chosen because of their relevance for ASSRs. While the difference between high and low carrier frequencies might have been more apparent with a 4000 Hz high carrier frequency, this would also give rise to smaller ASSR amplitudes. A modulation

frequency of 40 Hz was used because larger ASSR amplitudes and larger effects were expected with this modulation frequency [8].

Two experiments were conducted to compare loudness adaptation between modulated and unmodulated sinusoids. In the first experiment, sinusoidally amplitude-modulated sinusoids were used. In the second experiment, mixed-modulated sinusoids were used, containing both amplitude and frequency modulation.

MATERIALS AND METHODS

Participants

Fourteen healthy young adults (10 female, 4 male, 22.3 $\pm$ 3.1 years old) participated in the first experiment, and 15 other healthy young adults (13 female, 2 male, 21.7 $\pm$ 0.9 years old) participated in the second experiment. All participants provided informed consent in accordance with the declaration of Helsinki, and this project was approved by the ethical committee of the University Hospital of Leuven (UZ Leuven). None of the participants had ever participated in a loudness-related experiment before and all were unpaid volunteers. As determined by otoscopy, all participants had normal, unobstructed external ear canals. Pure tone audiometry on the left ear was performed before each test session with a Madsen Electronics Orbiter 922 audiometer and TDH-39 headset. All participants had normal hearing thresholds, 20 dB HL or better across all octave frequencies from 125 Hz to 8 KHz, with the exception of two participants who had a threshold of 25 dB HL at 8 kHz.

Apparatus and stimuli

The experiments took place in a soundproof booth. The software platform APEX 3, developed at ExpORL [13], was used for all experiments. Stimuli were created in Matlab R2013a (The Mathworks, Inc., Natick, MA) and presented to the left ear through an Etymotic Research ER-3A insert phone, connected to an RME Hammerfall DSP Multiface II sound card. The level of each stimulus was

separately calibrated in dB SPL using a 2cc Brüel & Kjær coupler. The right ear was plugged in order to minimize background noise and other distractions.

Each stimulus had a carrier frequency of either 500 or 2000 Hz and was presented at either 30 or 70 dB SL (sensation level). Three modulation types were used in the experiments: no modulation ('SIN'), sinusoidal amplitude modulation ('SAM'), and mixed modulation ('MM').

SAM stimuli were used in experiment I only and are described by the following formula:

$$y(t) = \sin(2\pi f_c t) * (0.5 + 0.5 * \sin(2\pi f_m t)) \quad (1)$$

where $y(t)$ is the stimulus amplitude at time t , f_c is the carrier frequency (500 or 2000 Hz), and f_m the modulation frequency (40 Hz).

MM stimuli were used in experiment II only. They contained both amplitude modulation and frequency modulation, and are described by:

$$y(t) = \sin\left(2\pi f_c t + \frac{0.25}{f_m} * \sin\left(2\pi f_m t - \frac{\pi}{2}\right)\right) * (0.5 + 0.5 * \sin(2\pi f_m t)) \quad (2)$$

where $y(t)$ is the stimulus amplitude at time t , f_c is the carrier frequency (500 or 2000 Hz), and f_m the modulation frequency (40 Hz).

Spectra of the stimuli are shown in Figure 1. Stimulus bandwidths were respectively 80 Hz and 240 Hz for the SAM and MM stimulus conditions.

In summary, each experiment consisted of 2x2x2 stimulus conditions: modulated (SAM in experiment I, MM in experiment II) or unmodulated (SIN) stimuli, with a carrier frequency of 500 or 2000 Hz, and presented at 30 or 70 dB SL. These stimulus conditions will be abbreviated as SIN/SAM/MM-500/2000-30/70. Total stimulus duration for the loudness adaptation experiments was always 302 s, and for hearing threshold determination 1 s.

Procedures

Hearing thresholds in dB SPL for each stimulus condition were determined using an adaptive three-interval, three-alternative forced-choice (3AFC) procedure. By

this procedure, three intervals were played consecutively, with three associated visual cues lighting up on a computer screen. Only one random interval contained the stimulus; nothing was presented in the other intervals. The participant was asked to indicate the number of the interval associated with the stimulus after each three-interval period. The level of the stimulus was adjusted based on a two-down, one-up rule, converging to 71% correct, with step sizes of 10, 5 and 2 dB after 0, 1 and 3 reversals respectively. After 6 reversals the threshold was calculated as the mean of the last 4 reversals. No feedback was provided to the participant.

After hearing threshold determination, stimuli were presented at 30 or 70 dB above the hearing threshold. Loudness adaptation was measured with a successive magnitude estimation task. During the course of a 302 s stimulus, participants had to rate its loudness at specific times by typing a self-chosen number related to the perceived loudness. A red visual cue alerted the participants to their task of typing this number. Loudness judgments were obtained in the form of this number, at 2 s after stimulus onset and at the end of each 20 s interval thereafter, for a total of 16 measurements. This was done for each stimulus condition in a random order, with the exception that two conditions with the same carrier frequency were never presented successively, to avoid residual adaptation effects due to stimulation of the same frequency without sufficient adaptation recovery time [14]. Participants were carefully instructed that they were free to choose a scale, to use any positive number, including decimals or fractions, and that the same number could be used multiple times. A zero would mean that the stimulus was inaudible. Moreover, the experimenter reminded the participants of the fact that an infinite range of other numbers lies between two given numbers and that there could be no wrong answers. No numerical examples were given.

Data Analysis

Similar to [6], [15]–[17], individual loudness adaptation percentages were calculated for each participant and stimulus condition as per the following equation:

$$\text{Loudness adaptation}_t (\%) = 100 * \frac{(E_t - E_0)}{E_0} \quad (3)$$

where E_0 is the number given 2 s after stimulus onset, and E_t the number given for the loudness judgment at time t . A positive percentage indicates loudness enhancement, a negative percentage indicates loudness adaptation. A loudness adaptation percentage of -100% ($E_t = 0$) indicates that the stimulus became inaudible, and a loudness adaptation percentage of 0% ($E_t = E_0$) indicates that neither adaptation nor enhancement occurred.

Statistical Analysis

Outliers were detected by the median absolute deviation or MAD-median rule [18]: a loudness adaptation percentage $X_{p,t}$ at time t of participant p was considered an outlier and removed from further analysis if

$$\frac{|X_{p,t} - M_t|}{MAD / 0.6745} > 2.24 \quad (4)$$

with M_t the median of the adaptation percentage across participants at time t of a particular stimulus condition and MAD the median of $|X_{1,t} - M_t|, \dots, |X_{N,t} - M_t|$, with N the number of participants.

Statistical analysis was performed using R [19]. A linear mixed-effects model was used to fit the combined data of experiment I and II. The model included the following predictors of loudness adaptation: time, the participant's threshold, the modulation type (SIN, SAM or MM), sensation level (30 or 70 dB SL), and carrier frequency (500 or 2000 Hz). These predictors were included in the model if judged to be an improvement according to the log-likelihood by analysis of variance (ANOVA). Interaction effects between predictors were also considered. The participant's intercepts and slopes were included as a random effect of the model. The SIN conditions of experiment I and II were combined and analyzed as a single stimulus condition. However, two contrasts were included to investigate the effect of modulation type by comparing SAM vs. SIN, to represent experiment I, and MM vs. SIN, to represent experiment II. Significance levels were set at $\alpha=0.05$, and in case of multiple comparisons, p-values were corrected based on Holm's method. To obtain an estimate of the final loudness adaptation percentage

of each stimulus condition, the data of each stimulus condition was fitted using polynomials. A linear polynomial was used for the basic fit, with second-order and third-order polynomials being used if they led to a better fit.

RESULTS

Estimated final loudness adaptation percentages

The results of the loudness adaptation experiments are shown in Figure 2. Based on visual inspection, loudness adaptation was only found at 30 dB SL, with more adaptation occurring at 2000 Hz. Most of the adaptation occurred in the first 150 s. At 30 dB SL and 2000 Hz, the final estimated loudness adaptation percentages, based on the fitted polynomials, were -65.8%, -53.6%, and -49.8% for the MM, SIN, and SAM modulation types respectively. This difference in loudness adaptation percentage between the three modulation types was more pronounced at 30 dB SL and 500 Hz, with estimated loudness adaptation percentages of -45.2%, -38.9%, and -10.9% for the MM, SIN, and SAM modulation types respectively.

In contrast, at 70 dB SL, small amounts of loudness enhancement were only found for the 500 Hz stimulus conditions. The final estimated loudness adaptation percentages were 9.2%, 13.7%, and 5.4% at 500 Hz, and -0.1%, -1.8%, and -5.1% at 2000 Hz for the MM, SIN, and SAM modulation types respectively.

Predictors of loudness adaptation

A summary of the linear mixed-effects model is shown in Table 1. Significant main effects were found for time, threshold, sensation level, carrier frequency, and the modulation contrast SAM vs. SIN. The modulation contrast MM vs. SIN was not significant. However, several interaction effects were found, and are described in the following sections.

Interaction effects between carrier frequency, modulation type, and sensation level

The interaction effects between carrier frequency, modulation type, and sensation level are shown in Figure 3 A-C.

Figure 3 A shows the significant interaction effect between sensation level and carrier frequency ($b=0.06$, $t(3127)=3.48$, $p=0.001$, see Table 1). At 70 dB SL, similar loudness adaptation percentages around 0% were found. In contrast, at 30 dB SL, more loudness adaptation was found for 2000 Hz compared to 500 Hz.

Figure 3 B shows the interaction effect between modulation type and sensation level. Only the interaction effect with the modulation contrast SAM vs. SIN was significant ($b=-0.07$, $t(3127)=-2.49$, $p=0.013$, see Table 1), which means that a significant difference in the slope of the SIN-SAM line was found between 30 dB SL and 70 dB SL. The p-value of the interaction effect with the modulation contrast MM vs. SIN was equal to 0.05. At 30 dB SL, MM stimuli showed more loudness adaptation than SIN stimuli, which in turn showed more loudness adaptation than SAM stimuli.

Figure 3 C shows the significant interaction effects between modulation type and carrier frequency ($b=-0.12$, $t(3127)=-5.50$, $p<0.001$ for the SAM vs. SIN contrast, and $b=-0.06$, $t(3127)=-2.60$, $p=0.009$ for the MM vs. SIN contrast, see Table 1). The difference between the modulation types was especially apparent at a carrier frequency of 500 Hz, with a more pronounced difference in slope for the SAM vs. SIN contrast.

Furthermore, only for the modulation contrast SAM vs. SIN, a significant interaction effect was found between sensation level, modulation type, and carrier frequency. Post-hoc analyses revealed no significant effects of time on loudness adaptation percentages, i.e. no loudness adaptation, for the 70 dB SL stimulus conditions and the SAM-500-30 stimulus condition (see Table 2).

In summary, while loudness adaptation only occurred at 30 dB SL and was observed for both carrier frequencies, significantly more loudness adaptation occurred at 2000 Hz. A difference was also found between modulation types, with more loudness adaptation for MM stimuli compared to SIN stimuli, and also more loudness adaptation for SIN stimuli compared to SAM stimuli. This difference between modulation types was more pronounced at 500 Hz and 30 dB

SL, with a disappearance of loudness adaptation for the SAM-500-30 stimulus condition.

Interaction effects between threshold and other predictors

The participants of experiment I had average thresholds of 7.4 dB SPL with a standard deviation of 5.9, and the participants of experiment II had average thresholds of 5.6 dB SPL with a standard deviation of 4.7 dB SPL.

As seen in Table 1, a significant interaction effect was found between the participants' threshold and the sensation level (see Figure 4). Only at 30 dB SL, the threshold had an influence on the loudness adaptation percentage, with lower thresholds leading to more loudness adaptation. Only one participant with a threshold of 19 dB SPL for the SIN-2000 stimulus had a deviant behavior. However, based on visual inspection, the adaptive staircase of this participant showed an unusual pattern. First, the staircase decreased to 5 dB SPL, with the lowest correctly detected threshold being 10 dB SPL. But thereafter the staircase increased again leading to a final estimated threshold of 19 dB SPL calculated as the mean of the last of 4 reversals. The participant might have been tired during the last trials and have had a lower true threshold.

The effect of threshold on loudness adaptation differed per modulation type, carrier frequency, and per combination of modulation and carrier frequency (see Table 1). In addition, the interaction effects between threshold, sensation level, modulation contrast, and carrier frequency indicate that the effect of threshold on loudness adaptation was different per stimulus condition. Therefore, correlation coefficients between the participant's thresholds and loudness adaptation percentages were calculated per stimulus condition. Moderate, but significant correlations were found for all stimulus conditions, except for the SAM-500-30 stimulus condition (see Table 3). In these calculations, all loudness adaptation percentages over time were included. The interaction effect between loudness adaptation percentage and threshold per stimulus condition is also shown in Figure 5. In the figure, each dot represents the average loudness adaptation

percentage corresponding to a certain threshold for one stimulus condition, with different colors showing different stimulus conditions.

In summary, although the stimuli were presented to each participant at the same sensation level, the participant's threshold and thus the stimulation level in dB SPL seemed to have an effect on the loudness adaptation percentage at 30 dB SL. Significant effects were found for all stimulus conditions at 30 dB SL, except for the SAM-500-30 stimulus condition.

DISCUSSION

The effects of carrier frequency, modulation type, and sensation level

In this study, we demonstrated that both sinusoidally amplitude-modulated and mixed-modulated sinusoids can cause loudness adaptation. However, differences in loudness behavior across modulation types were also found at 30 dB SL. MM stimuli gave rise to more loudness adaptation than SIN stimuli, which in turn gave rise to more loudness adaptation than SAM stimuli. A more pronounced difference between SIN and SAM modulation was found at 500 Hz, with a disappearance of loudness adaptation for the SAM-500-30 stimulus condition.

Loudness adaptation only occurred at the low sensation level of 30 dB SL. At the high sensation level of 70 dB SL, the same loudness behavior was found for MM, SIN, and SAM stimuli, with loudness enhancement percentages only present at the low carrier frequency of 500 Hz. Our results also showed more loudness adaptation for a higher carrier frequency, since all modulation types showed more loudness adaptation at 2000 Hz compared to 500 Hz. Furthermore, most of the loudness adaptation occurred in the first 100-150 s after stimulus onset. Thus, the results of this study are in agreement with many studies, e.g. [2], [6], [15]–[17], who also found more loudness adaptation at low sensation levels, high carrier frequencies, and in the first instants after stimulus onset.

The magnitude of adaptation was comparable to the results found in literature. Most similar to our stimuli are the 400 Hz and 2000 Hz pure tone stimuli presented at 30 dB SL used by Hellman et al. [17]. The final loudness adaptation

percentages for these stimuli after 367 s were -30% for both carrier frequencies. Although for these frequencies the percentages were similar; overall they found a progressive increase in adaptation with frequency. Tang et al. [6] described loudness enhancement effects at high sensation levels. Final estimated loudness adaptation percentages were 9.1%, 11.7%, and 6.7% for unmodulated sinusoids with carrier frequencies of 125, 1000, and 2000 Hz respectively, all presented at 90 dB SPL. The results are comparable with this study, although we only found loudness enhancement at low carrier frequencies.

In the literature, simple loudness adaptation has mainly been investigated with unmodulated sinusoids. Scharf [2] found the same loudness adaptation percentages for frequency-modulated stimuli as for their unmodulated counterparts. For amplitude-modulated stimuli, he found an increase in loudness adaptation when increasing the frequency separation of two tones centered on 4000 Hz. The loudness adaptation percentage saturated once the frequency separation reached the auditory filter bandwidth, and approached that of an unmodulated high-frequency tone. However, the final loudness adaptation percentage found by Scharf for frequency separations equal to or slightly larger than the auditory filter bandwidth was still slightly smaller compared to the final loudness adaptation percentage of the unmodulated high-frequency tone. Based on his findings, Scharf hypothesized that a change in excitation level within the auditory filter bandwidth in the cochlea can reduce or even eliminate loudness adaptation.

In our study, the different modulation types also yielded differences in stimulus bandwidths (see Figure 1). For SAM and MM stimuli, the bandwidth was 80 Hz and 240 Hz respectively. The auditory filter bandwidths for a center frequency of 500 Hz and 2000 Hz are 79 Hz and 241 Hz, respectively [20], and are indicated in gray in Figure 1. Based on Scharf's hypothesis, we would expect reduced loudness adaptation percentages when there is amplitude modulation within the auditory filter bandwidth. For bandwidths equal to or slightly larger or smaller than the auditory filter bandwidth, we would expect similar loudness adaptation

percentages or slightly reduced loudness adaptation percentages compared to their unmodulated counterparts.

First, for the MM-2000-30 and the SAM-500-30 stimulus conditions, with about equal bandwidths as the auditory filter bandwidths, we would expect the same or a slightly reduced amount of loudness adaptation as compared to their unmodulated counterparts. Indeed, the differences were small in the case of the MM-2000-30 condition. A statistically significant reduction in adaptation was found for the SAM-500-30 stimulus condition compared to the SIN-500-30 stimulus condition.

Second, for the MM-500-30 stimulus condition, with a bandwidth larger than the auditory filter bandwidth, we would also expect the same loudness adaptation percentage or a slightly reduced loudness adaptation percentage compared to the SIN-500-30 stimulus condition. Although the difference between MM-500-30 and SIN-500-30 was small, we found slightly more loudness adaptation for MM-500-30 than for SIN-500-30 (see also figures 2 and 3).

Third, for the SAM-2000-30 stimulus, with a bandwidth clearly smaller than the auditory filter bandwidth, we would expect a significant reduction in loudness adaptation. However, the SAM-2000-30 and SIN-2000-30 stimulus condition showed similar final loudness adaptation percentages. Our statistical analysis also showed only a small difference in modulation types at 2000 Hz. Interestingly, Scharf presented loudness adaptation percentages measured after 120s. As shown in Figure 2 in this study, a reduction in loudness adaptation percentages in the first 150s after stimulus onset was also found in this study. It seems that after around 150s, the amplitude modulations could no longer prevent loudness adaptation to occur.

Clearly, a dominant determinant for loudness adaptation to occur is the carrier frequency. Due to the tonotopic organization in the cochlea, more spread of excitation occurs for stimuli with low carrier frequencies compared to high carrier frequencies. This difference in spread of excitation in the cochlea might explain the difference in the reduction of loudness adaptation between SAM-500-30 and

SAM-2000-30 stimuli. The latter would also give further support to the restricted excitation pattern hypothesis, which many studies in literature already support (e.g., [2], [16], [17]). According to this hypothesis, loudness adaptation only takes place if the excitation pattern in the cochlea is spatially restricted and also temporally steady. The studies supporting the hypothesis always found loudness adaptation for specific stimulus parameters that lead to a narrow and steady excitation pattern in the cochlea, such as low sensation levels, high carrier frequencies, and pure tones [5], [21]–[23]. Compared to SAM stimuli, MM stimuli are spatially restricted, but the temporal changes in the excitation pattern might have been too fast to lead to a reduction in loudness adaptation.

Recently, Wynne et al. [12], also found reduced loudness adaptation for amplitude-modulated stimuli. A much higher carrier frequency of 12 kHz was used for all stimuli, which had a modulation frequency of 4, 20, or 100 Hz and were presented at 15 dB SL. Consequently, the bandwidths of these stimuli were always smaller than the auditory filter bandwidth, which is 1320 Hz for an unmodulated stimulus of 12 kHz. Regardless of the modulation frequency, the amplitude-modulated stimuli always showed a reduction in loudness adaptation after 180s, which corresponds to Scharf's hypothesis.

Wynne et al. proposed that reduced loudness adaptation might be due to an increased neural synchronization to amplitude modulations. Indeed, neural synchronization to amplitude-modulated stimuli is increased for auditory nerve fibers with higher characteristic frequencies [24]. However, a reduced loudness adaptation percentage was not found for mixed-modulated stimuli in this study, whereas MM stimuli evoke significantly larger ASSR amplitudes than SAM stimuli. This may indicate an increased synchronization somewhere on the auditory processing pathway for MM stimuli compared to SAM stimuli [25].

The differences in loudness adaptation between SAM and MM stimuli might be related to peripheral factors, central factors, or both. The role of central factors might be related to the observed difference between the processing of AM and FM stimuli in the auditory pathway up to the level of the supratemporal auditory

cortex (e.g., [26]). Further evidence for possible central mechanisms involved in loudness adaptation was also described by Tang et al. [6].

The finding that loudness adaptation occurs when using certain modulated stimuli, might have an impact on ASSR measurements in clinical and research practice, in which these stimuli are often used. Namely, it is possible that the ASSRs evoked by these modulated stimuli will suffer a decrease in amplitude over time. ASSRs evoked at low intensities, such as during the objective estimation of hearing thresholds, would most likely be influenced by adaptation. More research is needed to define whether loudness adaptation effects need to be considered in the ASSR and if so, to what extent this has clinical implications. If the ASSR amplitude is shown to be related with loudness adaptation, it might be better to use SAM stimuli instead of MM stimuli at low sensation levels and low frequencies.

The effect of threshold on loudness adaptation percentage

We also investigated whether the participants' thresholds had a significant influence on their loudness adaptation percentages. We found that thresholds only had a significant effect on the loudness adaptation percentages at 30 dB SL. Moderate, but significant correlations between the participants' thresholds and their amount of loudness adaptation were found for all stimulus conditions at 30 dB SL, with the exception of the SAM-500-30 stimulus condition, in which also no significant loudness adaptation was found. Participants with higher thresholds tended to show less loudness adaptation.

A moderate correlation between thresholds and loudness adaptation was also described by Scharf [2], although unclear results were reported. In a study including 39 participants with thresholds between -14 and 42 dB SPL, he did not find a correlation between thresholds and loudness adaptation percentages for a 4000 Hz stimulus at 10 dB SL presented in free field. However, in a study including 54 participants whose thresholds fell between 2 and 15 dB SPL in 80% of cases, he found a significant correlation of $r = 0.36$, with the stimuli presented through earphones. The range of thresholds of the latter study is more similar to

the range of this study. We found average thresholds of 7.4 ± 5.9 dB SPL, and 5.6 ± 4.7 dB SPL for experiment 1 and 2 respectively.

Thus, the thresholds of the participants or the stimulation level in dB SPL seems to play a crucial role in determining loudness adaptation. Differences in loudness adaptation percentage were found between participants, even when the sensation level was the same for all participants (30 dB SL). It would seem that the degree of adaptation is determined by absolute dB SPL values rather than sensation levels, meaning it would be better to use fixed dB SPL stimulation values instead of dB SL values in future loudness adaptation experiments, unless you want to differentiate between people. Intensities of around 40 dB SPL seem to be the limit for loudness adaptation for the stimulus conditions in this study (see Figure 5).

The occurrence of loudness adaptation at low sound pressure levels, irrespective of sensation level, might be related to the type of auditory nerve fiber activated. Auditory nerve fibers with a high spontaneous discharge rate (>20 sp/s) have lower thresholds for activation by acoustic stimulation than the auditory nerve fibers with low spontaneous discharge rates (<20 sp/s), and they also have a tendency to saturate within 30 dB of threshold [27], [28]. Loudness adaptation might mainly be caused by the high spontaneous discharge rate fibers. It has also been shown that auditory nerve fibers with low characteristic frequencies and high spontaneous discharge rates show the poorest envelope synchronizations for amplitude-modulated stimuli [24]. However, although neural adaptation (measuring over an interval of 192 s) was found in nerve fibers with both low and high spontaneous discharge rates in a study of Javel [29] in cats, more adaptation was found for nerve fibers with low spontaneous discharge rates, which seems contradictory. However, this neural adaptation is not necessarily related to the loudness adaptation phenomenon we observe in humans, e.g., more neural adaptation was also found at high sensation levels. More research is needed to investigate the contribution of the auditory nerve fiber types or other underlying physiological mechanisms and their relation with perceptual loudness adaptation phenomena in humans.

CONCLUSION

In this study, at 70 dB SL, small amounts of loudness enhancement were found for all modulation types at 500 Hz only. At 30 dB SL, loudness adaptation was found to occur for all modulation types, with more loudness adaptation at 2000 Hz compared to 500 Hz. Mixed-modulated sinusoids showed more adaptation than unmodulated sinusoids, which in turn showed more adaptation than sinusoidally amplitude-modulated sinusoids. The difference between modulation types was more pronounced at 500 Hz, with a disappearance of loudness adaptation for the sinusoidally amplitude-modulated stimulus condition at this carrier frequency. The fact that modulated stimuli can cause loudness adaptation might have implications for ASSR measurements, although this remains to be investigated. Furthermore, with the stimuli being presented at the same sensation levels to all participants, at 30 dB SL moderate but significant correlations were found between the participants' thresholds and their loudness adaptation percentages, with lower thresholds leading to more loudness adaptation.

List of figure captions

Figure 1: Frequency spectra of unmodulated sinusoids (SIN), sinusoidally amplitude-modulated sinusoids (SAM) and mixed-modulated sinusoids (MM). The dotted lines are the 500 Hz carrier stimulus conditions, the solid lines the 2000 Hz carrier stimulus conditions. The auditory filter bandwidths corresponding to each center frequency are represented by a gray shaded area.

Figure 2: The loudness adaptation percentages of the different stimulus conditions over time, shown per carrier frequency and sensation level. Unmodulated sinusoids (SIN) are indicated with dots, sinusoidally amplitude-modulated (SAM) conditions with crosses and mixed-modulated (MM) conditions with squares (and are blue, red and green respectively in the colored version). The SIN and MM data points are slightly shifted over the x-axis in order to increase the clarity of the figure. The best fitting polynomials for each stimulus condition are plotted in the form of thin lines on top of the data. Error bars indicate standard errors of the mean.

Footnote: We changed one response of one participant, even though it was not removed after the MAD-median rule. The participant gave the following responses for the SIN-500-30 stimulus condition each 20 s: [5 5 5 5 5 5 5 5 8 5 5 5 5 5 5]. In loudness adaptation percentages, this leads to [0 0 0 0 0 0 0 0 60 0 0 0 0 0 0]. Since it is unlikely that this participant really experienced a sudden enhancement of 60% in loudness, and we assume it might be a typing error (number 5 and number 8 are close to each other on a numeric keyboard), we decided to treat the “8” as an outlier, and removed it from further analysis.

Figure 3: The effects of sensation level, modulation type and carrier frequency on the loudness adaptation percentage. The mean loudness adaptation percentage indicates the mean of the loudness estimates over the specific times. Error bars indicate standard errors of the mean. The interaction effects are shown between (A) sensation level and carrier frequency, (B) modulation type and sensation level, and (C) modulation type and carrier frequency. The dashed line (blue in the colored version) indicates in (A) and (C) the 2000 Hz carrier frequency, and in (B) the 70 dB sensation level.

Figure 4: The effect of the participants’ thresholds on the loudness adaptation percentages for 30 and 70 dB SL. Each dot represents the average loudness adaptation percentage over all time points, corresponding to a certain threshold. The blue triangles represent the 70 dB sensation level, and the red circles the 30 dB sensation level.

Figure 5: The effect of threshold on the loudness adaptation percentage split up per carrier frequency, and per modulation type (only shown for the 30 dB sensation level). Each dot represents the average loudness adaptation percentage over all time points, corresponding to a certain threshold. Different colors represent different stimulus conditions. The SIN, SAM, and MM stimulus

conditions are plotted with blue squares, red triangles, and green circles respectively.

Tables and table captions

Table 1: Statistical details of the best fitting model for loudness adaptation including the combined data of experiment I and II. Each predictor's t-value, p-value, coefficient, and the 95% confidence interval (CI) of the coefficient are shown. Abbreviations: Mod. SAM = modulation contrast SAM vs. SIN, Mod. MM = modulation contrast MM vs. SIN, Sens. level = sensation level, Freq. = carrier frequency.

Predictor	t-value	p-value	Coefficient	95% CI	
Intercept	-4.382	<0.001	-4.405	-6.369	-2.442
Time	-9.593	<0.001	-0.145	-0.174	-0.115
Time x Threshold	6.070	<0.001	0.007	0.004	0.009
Time x Sens. level	16.356	<0.001	0.212	0.187	0.238
Time x Mod. SAM	5.939	<0.001	0.107	0.072	0.142
Time x Mod. MM	-0.388	0.698	-0.007	-0.042	0.028
Time x Freq.	-11.283	<0.001	-0.122	-0.144	-0.101
Time x Sens. level x Freq.	3.482	0.001	0.060	0.026	0.094
Time x Sens. level x Mod. SAM	-2.485	0.013	-0.066	-0.117	-0.014
Time x Sens. level x Mod. MM	1.942	0.052	0.048	0.000	0.096
Time x Mod. SAM x Freq.	-5.504	<0.001	-0.119	-0.161	-0.077
Time x Mod. MM x Freq.	-2.597	0.009	-0.055	-0.096	-0.014
Time x Sens. level x Mod. SAM x Freq.	2.772	0.006	0.095	0.028	0.163
Time x Sens. level x Mod. MM x Freq.	0.579	0.563	0.017	-0.041	0.076
Time x Threshold x Sens. level	-7.939	<0.001	-0.012	-0.015	-0.009
Time x Threshold x Freq.	1.962	0.050	0.003	1E-05	0.005
Time x Threshold x Mod. SAM	-2.843	0.004	-0.005	-0.009	-0.002
Time x Threshold x Mod. MM	-1.577	0.115	-0.003	-0.007	0.001
Time x Threshold x Sens. level x Freq.	1.597	0.110	0.003	-0.001	0.007
Time x Threshold x Sens. level x Mod. SAM	0.936	0.349	0.003	-0.003	0.008
Time x Threshold x Sens. level x Mod. MM	0.773	0.440	0.002	-0.003	0.008
Time x Threshold x Mod. SAM x Freq.	3.422	0.001	0.008	0.004	0.013
Time x Threshold x Mod. MM x Freq.	6.898	<0.001	0.019	0.014	0.025
Time x Threshold x Sens. level x Mod. SAM x Freq.	-2.288	0.022	-0.008	-0.015	-0.001
Time x Threshold x Sens. level x Mod. MM x Freq.	-3.442	0.001	-0.013	-0.020	-0.006

Table 2: Post-hoc analyses for the effect of time on loudness adaptation percentages for each stimulus condition involved in the SAM vs. SIN modulation contrast. All loudness adaptation percentages, at each time point, were used. The predictor time's t-value, p-value (corrected based on Holm's method), coefficient, and the 95% confidence interval (CI) of the coefficient are shown.

Stimulus condition	t-value	p-value (Holm corrected)	Coefficient
SAM-500-30	-1.239	0.868	-0.038
SAM-2000-30	-5.662	<0.001	-0.159
SAM-500-70	1.397	0.822	0.033
SAM-2000-70	-0.084	0.933	-0.002
SIN-500-30	-6.334	<0.001	-0.123
SIN-2000-30	-8.183	<0.001	-0.132
SIN-500-70	1.017	0.868	0.018
SIN-2000-70	-1.137	0.868	-0.023

Table 3: Correlation coefficients between the participants' thresholds and their loudness adaptation percentage per stimulus condition. All loudness adaptation percentages, at each time point, were used for the calculation of the correlation coefficients.

Stimulus condition	Correlation coefficient r	p-value (Holm corrected)
SAM-500-30	0.017	0.809
SAM-2000-30	0.414	<0.001
SIN-500-30	0.336	<0.001
SIN-2000-30	0.256	<0.001
MM-500-30	0.408	<0.001
MM-2000-30	0.309	<0.001

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Address for correspondence: Maaïke Van Eeckhoutte, KU Leuven, ExpORL, Department of Neurosciences, Herestraat 49, box 721, B-3000 Leuven, Belgium.

E-mail: maaïke.vaneeckhoutte@med.kuleuven.be

Fax number: +32 16 33 04 86

Telephone number: +32 16 33 04 88

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5