EVALUATING THE LOUDNESS EXPONENT FROM AUDITORY ADAPTATION DATA

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INTRODUCTION

The loudness exponent, *n*, defines the relationship between the intensity of a pure tone, φ, (measured, for example, in watt.cm^{-2}) and the loudness of the tone, *L*, (measured sometimes in units of *sones*, but in all cases dimension-free). In this paper we shall express φ as a dimensionless ratio, $\varphi / \varphi_{\text{thresh}}$, where φ_{thresh} is the threshold of the listener. 10 $\log_{10}$ $(\varphi/\varphi_{\text{thresh}})$ expresses the intensity of a tone as *sensation level* or SL. The equation that explicitly connects loudness with intensity is the power law of sensation, suggested by 19th century physicist, J. Plateau and further developed by 20th century psychologist S. S. Stevens:

$$L = k(\varphi/\varphi_{\text{thresh}})^{n} \tag{1}$$

In this equation, *k* is a scaling constant, greater than zero but otherwise arbitrary, that determines the magnitude of *L*.

The exponent, *n*, is of paramount importance in psychoacoustics. This exponent compresses the physical variable, intensity $(\varphi/\varphi_{\text{thresh}})$, which extends over a range of about 9 decades in everyday life (or 13 decades if one allows for rock concerts) into a range of only about 3 decades for the psychophysical variable, loudness, *L*. Stevens pioneered the technique known as *magnitude estimation*, whereby loudness is measured subjectively, by the listener's assigning a number to his or her impression of the loudness of a tone (e.g. "This tone has a loudness of 45 on a scale of 0 to 100.") Using this technique, the value of *n* has been found to be about 0.3 for all auditory frequencies between about 400 to 10,000 Hz. No difference in the value of *n* between genders had ever been reported prior to the studies by our group at the University of Toronto.

Our group has introduced techniques for measuring the *relative* values of *n* (females vis-à-vis males) without using classical subjective assessment such as magnitude estimation. Sagi, D'Alessandro and Norwich [1] showed that *n* could be evaluated to within a multiplicative constant by using a tone-intensity identification paradigm. Participants, who had been appropriately trained, were required to identify the dB intensity of unknown tones. From the *errors* made by these participants (signifying a loss of information between source and receiver), we were able to estimate the relative values of *n*. The calculation was straightforward. We found experimentally that participant-error, σ, was related to tone intensity, φ, by means of the linear relationship $\sigma = 2a\varphi + b$, where *a* and *b* are constant. We were then able to show that the exponent, *n*, was a simple multiple of the parameter, *a*. That is, for all subjects, we calculated $n = \lambda a$, where λ is an unknown constant of proportionality. For $\lambda = 4$, we obtained the expected values of *n*, but it was clearly not necessary to evaluate λ in order to show that the mean value of *n* for females exceeded the mean value for males. The gender difference is inherent in the parameter *a*; this difference is statistically significant.

It was evident to us, by 2006 that the auditory systems of males and females differed psychophysically to a marked degree. The mean value of *n* over all auditory frequencies was 0.3053 for females and 0.2218 for males. The mean female value exceeded the mean male value by 37.6%. So we set about the task of confirming our finding by an independent set of experiments.

METHODS

We proceeded this time to explore the process of loudness adaptation in a group of 14 participants, 7 male and 7 female, with mean age of about 22 years. Adaptation is the phenomenon wherein the loudness of a steady tone diminishes as the total duration of the tone increases. For example, very intense sounds tend to become less oppressive after an interval of time. Once again, magnitude estimation can be used to trace the course of loudness adaptation when a steady tone is applied to one ear for a protracted time interval. However, once again we eschewed this method in favor of the technique known as *simultaneous dichotic loudness balance*, or SDLB. This technique was conceived by von Békésy [2] and was named and developed by Hood [3]. It essentially uses one ear, the *control ear*, retained in silence, to monitor the level of adaptation in the other ear (the *adapting ear*) to which a steady tone is administered.

Experiments were conducted in a sound-attenuated booth. Steady tones were generated by an audiometer (Madsen Electronics, Micro 5) and administered to participants by means of headphones. Loudness thresholds were first determined in each participant using a Békésy staircase method. Thereafter, all sound intensity values were measured as dB SL, relative to each participant's own threshold. A steady tone of 50 dB SL (1000 Hz) was delivered to the adapting ear, and maintained for 370 s. After intervals of 0, 60, 120, 180, 240, 300 and 360 seconds, the participant was required to manually adjust the level of sound in the *control ear* until the tones in each ear were equally loud. This adjustment was completed in 10 s, after which the control ear was returned to silence and maintained in that state for 50s. After this 50s interval, participants repeated their loudness balance. In this way, they provided values for matching intensities, $\varphi(t) = \varphi(10), \varphi(70), \varphi(130) \ldots \varphi(370)$ progressively. These values of φ will be known as *intensities of adaptation.* Within a 1-h experimental session, participants made this series of loudness matches with two different tone intensities administered to the adapting ear: once with 50 dB SL and twice with 60 dB SL.

OBSERVATIONS

There are two ways in which one can report the magnitude of adaptation:

(i) Subtract the intensities of adaptation from the intensity of the applied tone to obtain *absolute adaptation*. In this way we calculate:

magnitude of adaptation to 50 dB tone = [50 – 50], [50 - $\varphi(10)$ dB], [50 - $\varphi(70)$ dB], …, [50 - $\varphi(370)$ dB], and,

magnitude of adaptation to 60 dB tone = [60 – 60], [60 - $\varphi(10)$ dB], [60 - $\varphi(70)$ dB], …, [60 - $\varphi(370)$ dB].

(ii) Subtract the intensities of adaptation from the intensity of the 10-second intensity of adaptation to obtain a measure of *relative adaptation*. In this way we calculate for each of 50 and 60 dB adapting tones

magnitude of adaptation = [$\varphi(10)$ dB - $\varphi(10)$ dB], [$\varphi(10)$ dB - $\varphi(70)$ dB] … [$\varphi(10)$ dB - $\varphi(370)$ dB].

Representative graphs showing these data (50 dB absolute adaptation and 60 dB relative adaptation) are given in Figures 1 and 2 respectively.

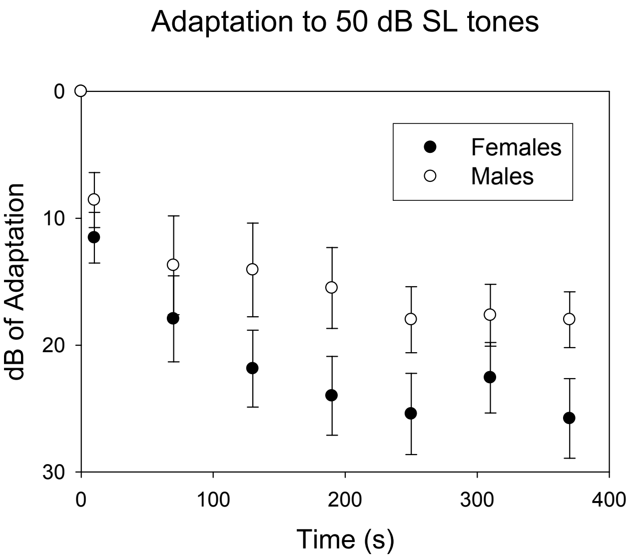

Figure 1: Absolute Adaptation. dB of adaptation (calculated with respect to the 50 dB reference intensity) versus time averaged over all 7 female and all 7 male participants

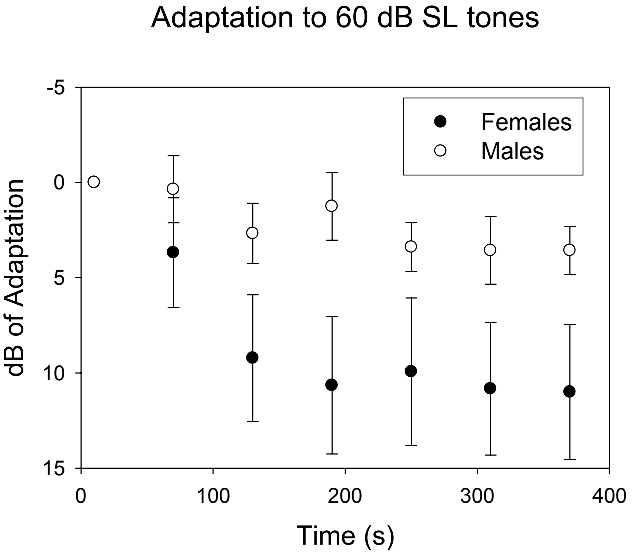

Figure 2: Relative Adaptation calculated with respect to the 10 s reference intensity) versus time averaged over all 7 female and all 7 male participants

ANALYSIS

Certain features of the data are immediately apparent. In both the absolute and relative modes of calculation, females adapt more completely than males of the same age. The difference in the magnitude of adaptation between females and males at the final (370 s) time point is statistically significant, $p < 0.05$. Although not reported by earlier researchers, the variable, $\varphi(t)$, which measures the extent of adaptation, seems to oscillate about an asymptote, rather than decline monotonically. There are several reasons to believe that these are true oscillations and not noise in the data. Perhaps the most compelling is that when a given participant was tested on two different days, often separated by one week or more, he or she would replicate their initial loudness balances quite closely.

The theory underlying the calculation of the value of the exponent, *n*, from adaptation data would take us rather too far afield. Some of the theory appears in the thesis by D'Alessandro [4]. It is discussed in more detail in the full journal paper [5]. However, the bottom line is straightforward. The value of *n* may be estimated from the ratio of the maximum adaptation in decibels to the magnitude of the applied tone in decibels. Thus, for example, from Figure 1 it may be seen that maximum absolute adaptation for males is about 20 dB in response to a 60 decibel adapting tone. The value of *n* may then be estimated as 20/60 = 0.33. The method was modified slightly for calculations from relative adaptation data. Calculations are summarized in Table 1.

Table 1: *n*-values calculated from our model using adaptation data from the present study (1000 Hz)

	***n*-values**					
	Absolute (0 s reference)			***Relative (10 s reference)***		
dB tone	***Females***	***Males***	***Avg.***	***Females***	***Males***	***Avg.***
50 dB SL	0.52	0.36	0.44	0.37	0.26	0.32
60 dB SL	0.49	0.32	0.41	0.26	0.09	0.17
Avg. over gender	0.50	0.34	0.42	0.32	0.18	0.25

DISCUSSION

We observe that at each intensity and for both absolute and relative adaptation the mean values of *n* for females again exceed those for males. This result is in consonance with our previous studies on *n* (see above) [1].

There were a number of papers published during the past half-century offering a detailed study of the SDLB technique used here. We selected two studies whose experimental protocols were most similar to our own; although these studies did not select gender as a variable, they reported data from test tones ranging from 30 to 90 dB, and sometimes over many auditory frequencies. These were papers by Jerger [6] and Weiler *et al.* [7].

Jerger [6] measured auditory adaptation at 7 frequencies and 7 intensities. At 1000 Hz, he measured adaptation at intensities ranging from 30 to 90 dB SPL, inclusive, in 10 dB SPL increments (i.e., at 30, 40, 50, 60, 70, 80, and 90 dB SPL). As mentioned earlier, many of the characteristics of his SDLB experiment were similar to ours. He employed a 15 s on-time and 45 s off-time (cf. 10 s on-time, 50 s off-time used presently). The adapting stimulus was 5 min long (cf. 6 min in our study). His participants were instructed to use midplane localizations (adjusting the intensity of the sound until is seems localized in the midplane), instead of loudness balances; however Weiler and Blackmond [8, p. 102] report that the two techniques give similar adaptation results. Decibels of adaptation were calculated with respect to a 15 s point.

Similarly, Weiler *et al.* [7] report dB of adaptation -- also measured using the SDLB technique -- for 5 stimulus levels in the range 40-80 dB SPL at 1000 Hz; that is, at 40, 50, 60, 70, and 80 dB SPL. His group used 10 s on-times and 50 s off-times. The adapting stimulus was 7 min long. Decibels of adaptation were calculated with respect to a 10 s point.

The value of the exponent, *n*, is calculated in the same manner as used on our own data, however, not all the required data were provided explicitly in these papers. For example, the matching intensities for the 10s (or 15 s) point are not given. SPL rather than SL was used. We worked around the missing data; but the reported results are correspondingly approximate and the resulting *n*-values will be slightly lower than our own values. The calculated values for *n* at various intensities are shown in Table 2 from the data of Jerger [6] and Weiler *et al.* [7].

Table 2: Loudness exponents from data of Jerger [6] and Weiler *et al.*, [7] (1000 Hz)

	***n*-values**	
dB tone	***Jerger [6]***	***Weiler* et al. [7]**
30	0.37	-
40	0.33	0.31
50	0.34	0.30
60	0.36	0.34
70	0.29	0.29
80	0.31	0.27
90	0.30	-
Avg.	0.33	0.30
St. Dev.	0.028	0.025

SUMMARY

A study of apparent adaptation using the SDLB technique revealed that young women adapt to steady tones to a greater extent than men of the same age. The adaptation data can be used to estimate values for the power function exponent, *n*, that are usually measured by magnitude estimation. The calculated values of n reveal that n is significantly larger in females than in male, a result that confirms our earlier study. The same technique of calculation applied to the data of other researchers produced nominal values for n as well.

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