Specific frequency band contributions to the loudness of broadband sounds

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ABSTRACT

The contribution of individual frequency bands to the loudness of broadband noise was determined in two tasks for six subjects with normal hearing (NH) and five with sensorineural hearing loss (SNHL). Stimuli were equated for audibility for all subjects. In the first task, subjects matched the loudness of variable bandwidth noises (comprised of sets of 2-ERB wide noise-bands) to a reference noise to determine the contribution of each additional 2-ERB wide noise-band. In the second task, subjects compared the loudness of pairs of wideband (375-6239 Hz) noises where the level of each 2-ERB wide band varied individually from trial to trial. Results in the matching task were similar for NH and SNHL listeners. Both groups showed an orderly increase in loudness level as the number of noise bands increased. Results in the second task indicated that subjects with NH put increased weight on high-frequency bands compared to SNHL listeners, despite similar loudness matching results in the first task. These data provide additional insight into the differences in frequency weighting between NH and SNHL listeners and may aid in understanding the role of SNHL in altering the loudness perception of broadband sounds.

INTRODUCTION

Despite the emphasis on loudness in hearing-aid design and hearing-aid fitting algorithms, loudness measurements are rarely made when fitting hearing aids (Cox, 2010) and loudness concerns remain an important factor in the rejection of hearing aids. We lack a complete understanding of the rules governing the contributions of individual frequency bands to the total loudness of a broadband sound. Current loudness models (e.g., Moore et al., 1997; Moore and Glasberg, 2004) are primarily based on data obtained with narrow-band sounds and on excitation patterns derived from masking studies.
Previous data sets for the loudness of broadband noise are limited (Zwicker et al., 1957; Pollack, 1951, 1952; Stevens, 1956; Bonding and Elberling, 1980; Chalupper and Fastl, 2002).

The first aim of the present study was to determine the relative impact of adding low and high bands to a noise on the loudness of the noise, assessed through a loudness-matching paradigm. These matches are compared to predictions made by a loudness model (Moore and Glasberg, 2004) in subjects with NH and SNHL. The contributions and relative weighting of individual noise bands to the loudness of broadband noise was then assessed in subjects with NH and SNHL using a sample- discrimination task and compared to model predications. The goal of this study was to answer the question of what frequency regions make the greatest contributions to the total loudness of a stimulus, which will aid in the optimization of hearing-aid strategies which use loudness criteria in their fitting.

EXPERIMENT 1:

Loudness matches between varied-bandwidth noise and a comparison 10-ERB wide noise band

The goal of the first experiment was to determine the difference in level required to match the loudness of a reference bandwidth of noise and a comparison noise which varied in bandwidth.

Subjects
The subjects were 11 adult paid-volunteers, 6 with NH (all females) and 5 with SNHL (2 male, 3 female). The mean age for the subjects with NH was 23.5 years and the mean age for subjects with SNHL was 56.8 years. NH subjects had thresholds < 20 dB HL for all tested frequencies.

Stimuli and equipment
The stimuli were noises of varying bandwidth comprised of individual 2-ERB wide bands. The narrowest was a single 2-ERB wide band from 1546-1972 Hz. Noises of increasing bandwidth were created by adding 2-ERB wide bands above and below until the widest condition, a 22-ERB wide noise (375-6240 Hz) was reached. The noise conditions used for the study are reported in **Table 1**. All stimuli were presented for 200 ms, including 10-ms, cos^2, onset/offset ramps.

Stimuli were generated digitally in Matlab at a 44.1-kHz sampling rate and were played through 24-bit digital-to-analog convertors (DAC) (Digital Audio Labs, CardDeluxe). A remote passive attenuator coupled the outputs of the DAC with Sennheiser HD250 Linear II headphones. Stimuli were delivered to the left or right ear (depending on the subject's better ear) in a double-walled sound-attenuated booth.

Procedure
Thresholds were first estimated for each 2-ERB wide noise in quiet using a 2IFC adaptive procedure with decision rules that estimated the 71% point on the psychometric function. Subjects completed two blocks of 50 trials for each ascending 2-ERB noise band. The estimated thresholds for all subjects are shown in **Figure 1**. Because audibility was a concern, customized stimuli were generated which preserved levels of 20 dB sensation level (SL) per band for each subject. Loudness matches were made between the reference 10-ERB wide noise and noises of other bandwidths using a two-track, 2IFC adaptive loudness procedure (Jesteadt, 1980).

The loudness matches for each block of trials for each condition were generated by averaging the estimated 71% and 29% points on the psychometric function. The data that are presented are the mean of the resulting matches for the tracks where the reference condition was shifted relative to a fixed-level comparison band.

Results
The loudness matches for subjects with NH and SNHL are shown in **Figure 2**. An orderly increase in the level of the 10-ERB reference band is seen for all subjects. A best-fit linear regression was determined for each subject's matches to the symmetric noises (those centered on bands 11 and 12) The slope and goodness of fit to the data are shown in **Figure 2**. **Figure 3** shows the mean and SD of the slope across subjects with NH and SNHL. Both groups have similar mean values, but the subjects with SNHL have widely variable slopes The shift in level of the 10-ERB reference band when either a low or high frequency band was added to a symmetrical noise is shown in **Figure 4**. Data from the subjects with NH show that both the low and high bands contribute nearly the same amount of loudness in all but the narrowest condition where the high band is contributing more to the overall loudness than the low band. Data from subjects with SNHL are more varied. Loudness matching data predicted by a model of loudness (Moore and Glasberg, 2004) for individual subjects with SNHL and for the mean levels presented to subjects with NH are shown in **Figure 5**. The correlation between the model and the SNHL subject data are > .90 in all but 1 subject with SNHL (SNHL 2). The agreement between the model and the NH data is higher (r = .99). For subjects SNHL 2 and SNHL 3, the model over predicts the loudness match levels in broadband conditions (> 14 ERBs wide).

EXPERIMENT 2:

Perceptual weighting of individual components of a 22-ERB wide broad band noise

The primary goal for the second experiment was to determine the perceptual weight for each 2-ERB band of the 22-ERB wide noise. Perceptual weights provide a measure of the relative contributions of the frequency bands to the total loudness of the complex. The weights were measured using a two-interval loudness-judgment task.

Subjects
The same subjects who participated in Experiment 1 participated in Experiment 2.

Stimuli and procedure
The quiet thresholds measured for each noise band in Experiment 1 were used to generate individual noise bands centered 10, 20 and 40 dB SL for each band. Subjects with NH completed the perceptual weights experiment at all three levels and subjects with SNHL completed 10 and 20 dB-SL conditions if the stimuli could be presented within the dynamic range of the lab's equipment (max SPL 105 dB).Eleven-band complexes were presented in each interval. The levels of the individual components were selected at random from a rectangular distribution of levels with a range of 16 dB and a step size of 1dB for a SD of 4.61 dB.

Subjects were instructed to pick the louder interval, but one interval, chosen at random, was incremented by 3 dB to create a sample-discrimination task. Ten 100-trial blocks were completed for each SL condition. The timing intervals were the same as was used in Experiment 1. Subjects were not provided with any correct-answer feedback. A description of the paradigm is shown in **Figure 6**. The 20 dB SL condition of subject NH 1 is shown for reference, with level perturbations of the individual noise bands for an individual trial.

Data analysis
Perceptual weights were calculated for each individual subject using the linear-regression model, as described by Lutfi (1995),

$$D = \sum w_i x_i + C,$$

where D is the response of the subject, x_i is the difference between the two levels of the same ith component across the two intervals, w_i is the weight of the ith component and C is a constant. In this case, C is a measure of internal noise, which occurs both before and after a subject's weights are applied. Two separate multiple-regression analyses were completed with the reference signal in interval 1 and with the reference signal in interval 2. The resulting weights were averaged and normalized such that they summed to 1 for all 11 components.

Results
Results of the perceptual weights analysis are shown in **Figure 7**. Predictions by the loudness model (Moore and Glasberg, 2004) are shown by a red line. Data for subjects with NH reveal an emphasis on the lowest and highest band in the complex. The pattern of weights does not change significantly with level. A two-way ANOVA with component and SL per band as independent variables and normalized weight as a dependent measure reveals a significant effect of component [$F_{(10,132)}$ = 8.18 p <.001] but not SL per band nor the SL per band by component interaction (p > .05). Post-hoc Tukey-Kramer HSD testing indicates that the weight given to bands 1 and 11 were significantly higher than those given to the other bands (p < .01).

Analysis of the weights data for subjects with SNHL using the same ANOVA design indicates a significant effect of component [$F_{(10,65)}$ = 5.04 p <.001], but not SL per band nor the SL per band by component interaction (p > .05). Post-hoc Tukey-Kramer HSD testing indicates that the weight given to band 1 is significantly higher than those given to the other bands (p < .01). Data for only 2 subjects at 20 SL per band were included due to dynamic-range issues, but the pattern of weights for the subset of 2 subjects is similar to that of the full group of 5 subjects with SNHL.

The loudness model does not generally agree with the subject data. For subjects with NH, the model predicts assignment of approximately equal weight to all bands and does not predict the low- and high-frequency emphasis observed in subjects. For subjects with SNHL, the model predicts a large high-frequency emphasis that is not observed in the data.

DISCUSSION

The data shown are preliminary. The number of subjects tested is small and large variability in loudness matching slopes amongst the subjects with SNHL was seen. Results obtained with the model show good agreement with observed matching data for both subjects with NH and those with SNHL, but tend to not agree with observed perceptual weights.

This set of data shows that the relative contributions of individual noise bands to the loudness of a broadband sound are different between subjects with NH and those with SNHL despite stimuli being equated for audibility across all bands. In general, subjects with NH place more weight on the lowest and highest bands of the complex, while subjects with SNHL have only a low-frequency emphasis to their loudness judgments.

KEY: Asymmetrical Band; Center Band; Symmetrical Band; Band ID

# ERB																							Lower freq.	Higher freq.
2											11	12											1546	1972
4									9	10	11	12											1202	1972
4											11	12	21	22									1546	2502
6									9	10	11	12	13	14									1202	2502
8							7	8	9	10	11	12	13	14									925	2502
8									9	10	11	12	13	14	23	24							1202	3158
10 REF CONDITION							7	8	9	10	11	12	13	14	15	16							925	3158
12					5	6	7	8	9	10	11	12	13	14	15	16							701	3158
12							7	8	9	10	11	12	13	14	15	16	17	18					925	3973
14					5	6	7	8	9	10	11	12	13	14	15	16	17	18					701	3973
16			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18					521	3973
16					5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			701	4984
18			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			521	4984
20	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			375	4984
20			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	521	6240
22	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	375	6240
	1		2		3		4		5		6		7		8		9		10		11			

Table 1. Loudness matching conditions. Bandwidth is given in ERBs and Hz. The 10-ERB wide reference condition is highlighted.

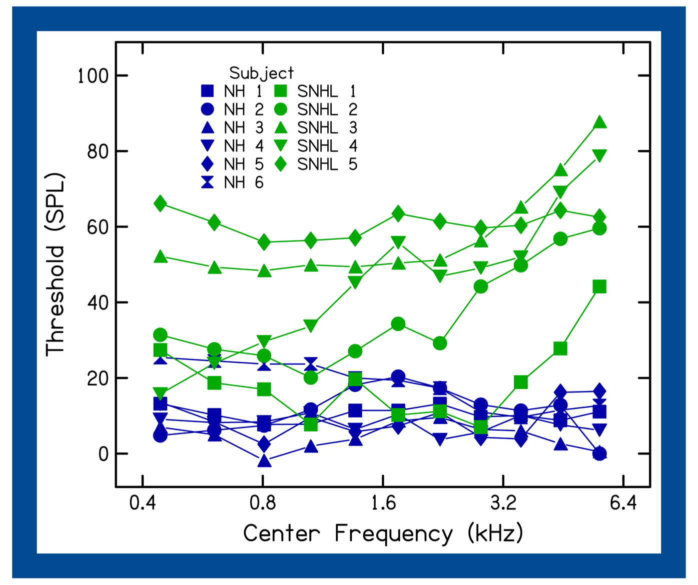


Fig. 1. Absolute thresholds for 6 NH and 5 SNHL subjects for each of the 11 2-ERB wide noise bands used in the experiments.

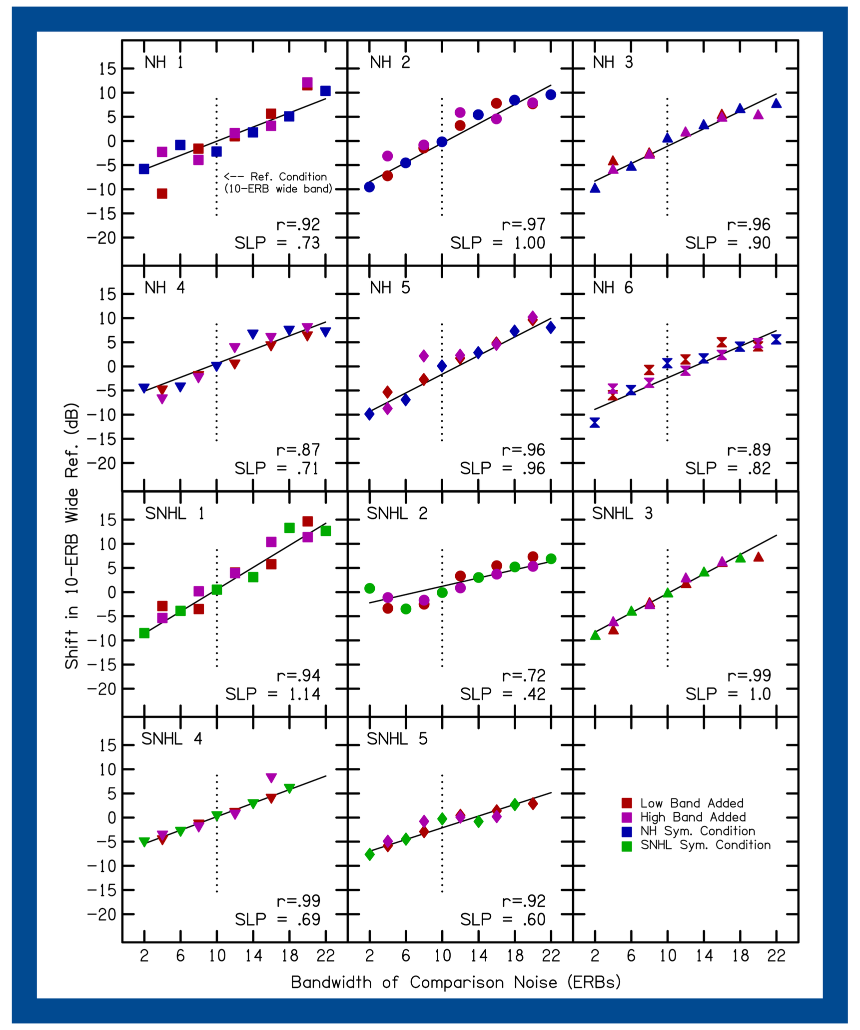
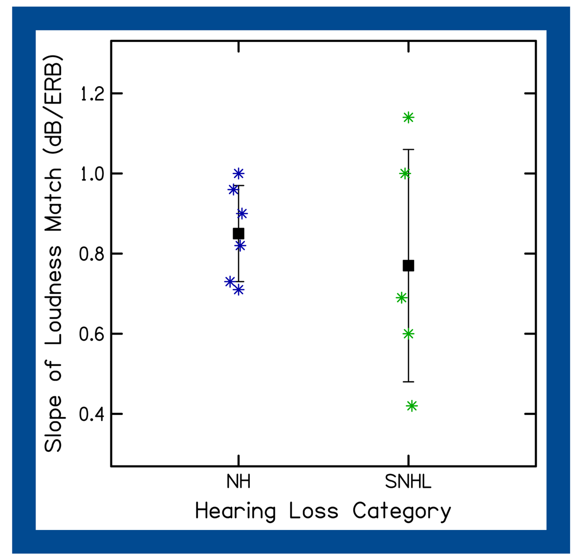


*Fig. 2. Subjects matched the loudness of a 10-ERB wide reference band of noise to the loudness of a noise ranging from 2-ERB wide to 22-ERB wide. The resulting shift in the level of the 10-ERB reference is shown for subjects with NH and those with SNHL. A best-fit linear regression to symmetrical conditions (see **Table 1**) is shown along with individual slopes and goodness of fit. All subjects show an orderly increase in the level of the reference as the comparison noise increases in bandwidth. Subjects with SNHL show greater variability in slope compared to NH listeners.*

Fig. 3. The mean, SD, and individual subject's slope of loudness matching are shown for subjects with NH and those with SNHL. Subjects with SNHL show a slightly shallower mean slope but the data are highly variable in the SNHL group.



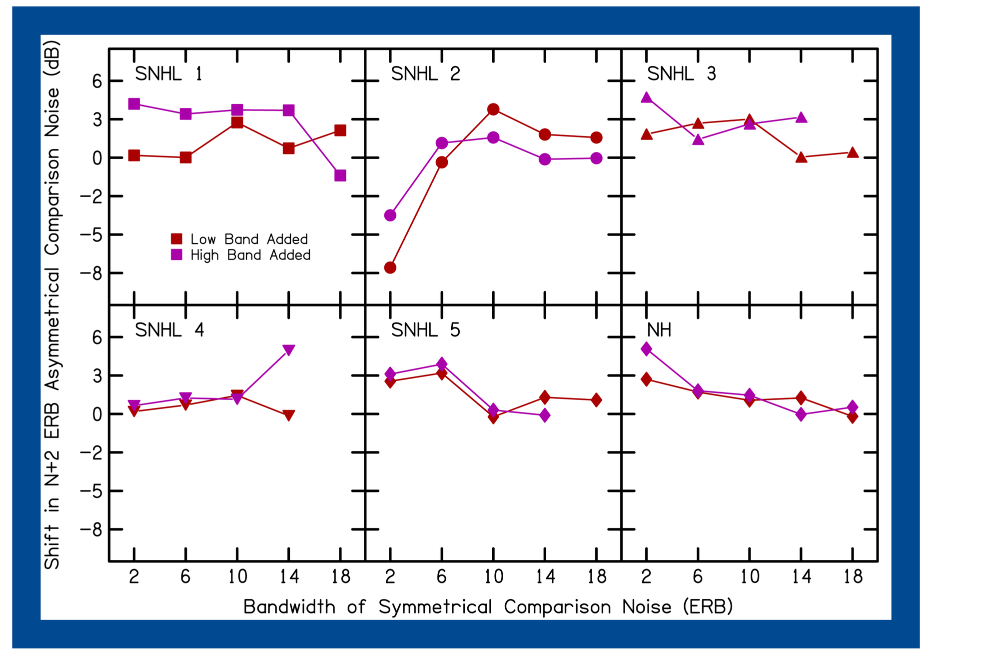


Fig. 4. Asymmetrical matching conditions. The shift in the level of the 10-ERB wide reference noise is shown when a single low or high band is added to a symmetric noise. Mean data from subjects with NH are shown as well as individual data from 5 SNHL subjects.

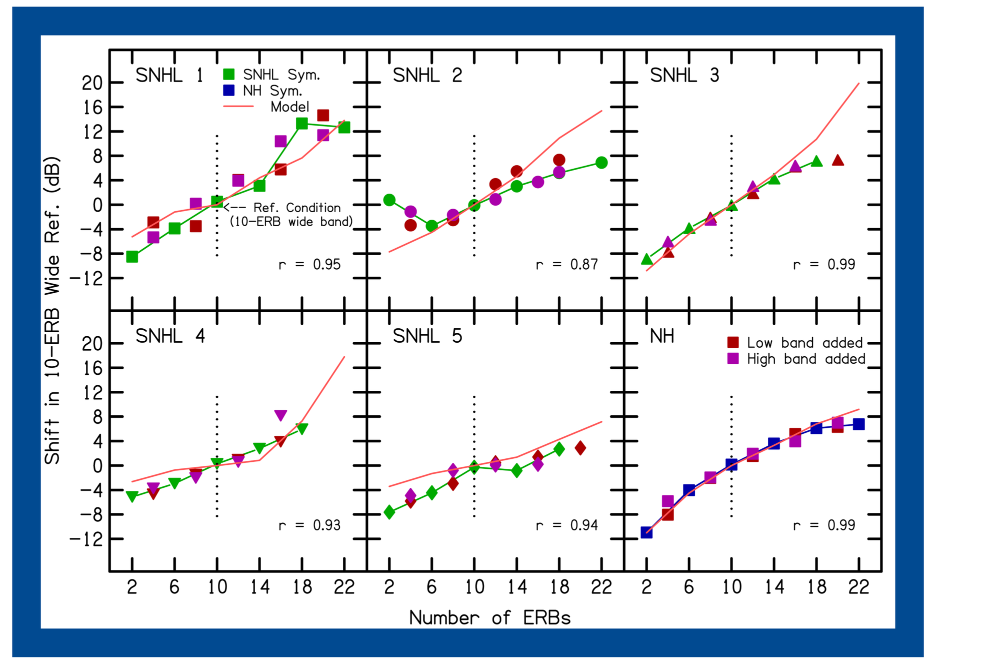


Fig. 5. Individual matching data for 5 SNHL subjects along with mean matching data from 6 NH subjects are shown plotted with predictions made by the Moore and Glasberg (2004) loudness model. Correlations between the model and data are shown.

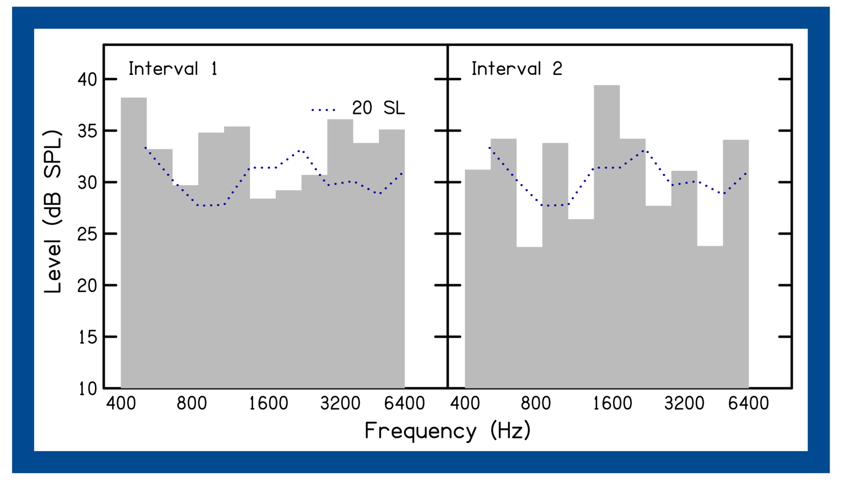


Fig. 6. In the perceptual weights sample-discrimination task, subjects voted which of the 22-ERB wide complexes was louder. Components were presented simultaneously and the level of each component was selected from a rectangular distribution with a range of ± 8 dB from a subject's SL for a current condition. This figure shows the 20 SL profile for NH 1 as well as two noise complexes. Interval 1 is the randomly selected signal interval, which also included a mean difference of 3 dB from interval 2.

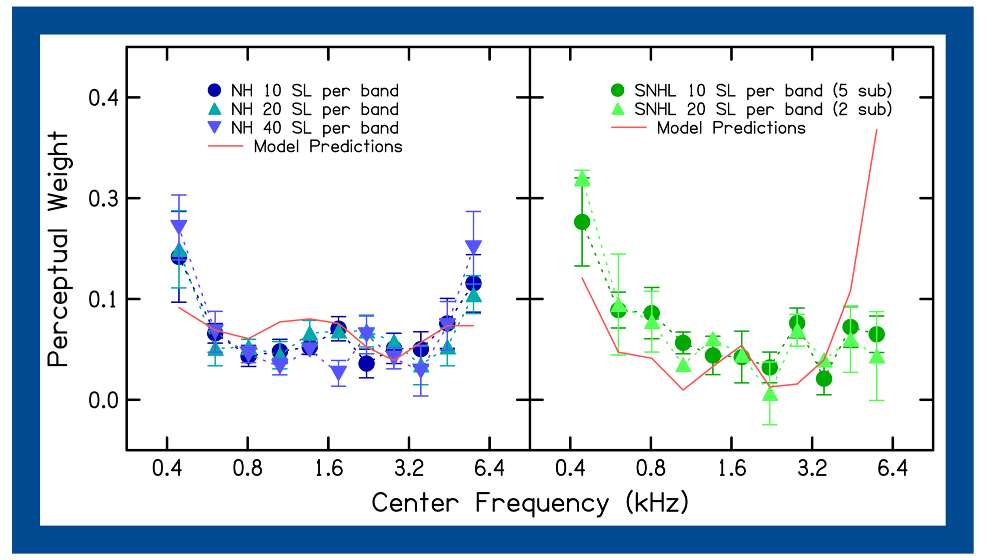


Fig. 7. Comparison of weights obtained from loudness judgments at 10, 20 and 40 SL for subjects with NH, as well as 10 SL for subjects SNHL 1-5 and 20 SL for SNHL 1 and 2. The data are based on 1000 2-interval trials per level. Each point represents the mean and standard error for the perceptual weight. Model predictions are show by a red line.

SUMMARY AND CONCLUSIONS

- Perceptual weights provide a valid measure of the contribution of individual frequency regions to overall loudness.
- Perceptual weights of a broadband noise did not depend highly on the overall level of the complex (10, 20, or 40 SL per band for subjects with NH; 10, 20 SL per band for subjects with SNHL).
- Subjects with NH placed increased weights on the lowest and highest band in the 22-ERB wide complex whereas subjects with SNHL placed increased weight on the lowest band only, despite the stimuli being equated for audibility in all conditions.
- Good agreement was found between matching data and data predicted by the Moore and Glasberg (2004) loudness model for both subjects with NH and those with SNHL.
- The Moore and Glasberg (2004) model under predicts the contributions of the low- and high-frequency bands in the perceptual-weights experiment for subjects with NH and over predicts the contributions of the highest band to loudness in subjects with SNHL.

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