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Using hearing threshold-simulating noise to explore differences in speech intelligibility and listening effort between noise and quiet

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Abstract

Recent studies have shown significant differences in speech intelligibility and subjective listening effort between noisy and quiet environments. In this study, it was therefore investigated whether these differences can be explained by assuming that an internal noise limits speech perception in quiet at low levels. To explore this, psychometric functions of subjective listening effort and speech intelligibility were assessed in 18 normal-hearing participants using a noise spectrally matched to the hearing threshold. The hearing threshold-simulating noise (HTSN) at 70 dB SPL was compared to standard OLnoise at 60 dB SPL. The results indicate that differences between measurements in noise and quiet cannot fully be explained by assuming that soft speech is masked by internal noise different from that used during speech-in-noise tests. Future research should investigate potential cognitive effects beyond internal noise masking (HTSN) that influence speech intelligibility and listening effort in quiet.

I. Introduction

In audiological research, speech intelligibility and listening effort are typically studied in background noise to simulate realistic conditions. These studies reveal how acoustic environments affect hearing and key factors influencing intelligibility and effort [1], [2]. In Germany, the Oldenburg Sentence Test (OLSA) [3] is commonly used to measure speech intelligibility, while the Adaptive Categorical Listening Effort Scaling (ACALES) [4] assesses listening effort.

As shown by Krüger et al. [1] and Kemper et al. [2], subjective listening effort peaks at around 50 % speech intelligibility and decreases with higher speech levels or signal to noise ratio (SNR). The lowest effort occurs at both very low and near-maximum intelligibility.

Denk et al. [5] observed a trend in subjective listening effort across noise levels: at lower noise levels, ACALES curves shifted towards higher speech intelligibility and flattened. A recent study inspired by Denk et al. investigated subjective listening effort and speech intelligibility at soft speech levels in quiet [6], [7]. Results indicate that in quiet, ACALES curves are flatter, with the maximum shifted to around 90 % speech intelligibility in young normal-hearing subjects. This highlights a wide range of levels where listening remains effortful despite full intelligibility, requiring much higher levels to significantly reduce effort.

This work explores the causes of differing results between measurements in noise and quiet. A key question is whether internal noise at the hearing threshold limits speech intelligibility at low levels in quiet. If so, these deviations may stem from differences between internal noise and the spectrally matched OLnoise of the OLSA. Additionally, it examines whether other factors, such as level-dependent auditory processing, influence measurements in quiet.

II. Methods and materials

II.I. Participants

This study included 18 young adults with normal hearing, defined as a pure-tone threshold of ≤ 20 dB from 125 Hz to 8 kHz. The participants (5 men, 13 women; aged 19–29 years; mean: 23.8 years; SD: 2.6 years) were recruited via the University of Lübeck's mailing list, private contacts, and employees of the German Institute of Hearing Aids in Lübeck.

II.II. Study Setup

In this study the speech reception threshold (SRT) and perceived listening effort were recorded. Measurements were conducted using the Oldenburg Measurement Application (OMA, Version 2.3.2.0). The Oldenburg Sentence Test (OLSA) [3] determined the SRT, while listening effort was assessed with the Adaptive Categorical Listening Effort Scaling (ACALES) [4]. Listening tasks were presented via a Genelec 8351 coaxial loudspeaker. The examiner, outside the test room, monitored OLSA responses in real time using a Sennheiser MKE 600 directional microphone and HD 280 Pro headphones.

II.III. OLSA and ACALES

During OLSA and ACALES measurements, the noise level remained constant while the speech level was adaptively varied. Both tests use standardized sentences with the structure: name - verb - number - adjective - object [3], and share the same language material. The OLSA enables the determination of various speech intelligibility thresholds, such as SRT50, where 50 % of the presented speech material is correctly understood.
For young adults with normal hearing, the SRT50 in OLnoise is -7.1 dB ± 1.1 dB SNR with a slope of 17.1 dB/%. In quiet (monaural presentation), the slope is flatter at 11.3 dB, and the SRT50 is 19.9 dB ± 2.8 dB. Speech intelligibility across different SNR values forms a psychometric function, which is nearly linear between 20 % (SRT20) and 80 % (SRT80) intelligibility [8]. During ACALES, participants rate listening effort on a scale from Effort Scale Categorical Unit (ESCU) 1 ('no effort') to ESCU 13 ('extreme effort'). A non-linear model curve is established, describing the relationship between listening effort and SNR [6]. Reference data for ACALES in OLnoise at 65 dB SPL show approximate SNR values of 9.5 dB for ESCU 1 and -8 dB for ESCU 13 in young adults with normal hearing [4].

II.IV. Stimuli

Two noise signals were used as stimuli: the default spectrally matched noise (OLnoise) and an hearing threshold-simulating noise (HTSN) specifically created for this study. Similar to Jürgens et al. [9], the HTSN simulates internal ear noise, but instead of individual thresholds, it is based on ISO 389-7 [10], representing the hearing threshold of young adults with normal hearing. The HTSN was generated using hearing threshold values from 100 Hz to 10 kHz, with one-third octave band weighting. Uncorrelated pink noise signals for 21 frequency bands were scaled to their respective thresholds and combined into broadband noise. RMS and duration were matched to OLnoise, and both signals were calibrated in the OMA software to the same level (dB SPL) at a measurement distance of 70 cm. A pilot study with five measurements per noise signal at 60 dB SPL fixed noise levels showed the SRT50 for HTSN (-17.8 dB SNR) was approx. 10 dB SNR lower than OLnoise (-7.8 dB SNR). For the main study, the OLnoise level was set to 60 dB SPL and the HTSN to 70 dB SPL to ensure comparable speech levels at the SRT. Fig. 1 shows the one-third octave band levels of the HTSN (blue curve, 70 dB SPL) and OLnoise (red curve, 60 dB SPL) used in the experiment. It also displays the hearing threshold defined in ISO 389-7 [10] (pink dotted curve) for free-field measurements from 0°. The shifted hearing threshold curve (black dashed curve) is included to highlight the correspondence between the hearing threshold and HTSN. The distance between the hearing threshold and the shifted curve is approx. 41 dB SPL. Considerable differences appear below 250 Hz and above 4 kHz, where the HTSN exceeds the OLnoise level. In the 250 Hz to 700 Hz range, the OLnoise level is higher, with a maximum difference of 4 dB at around 400 Hz.

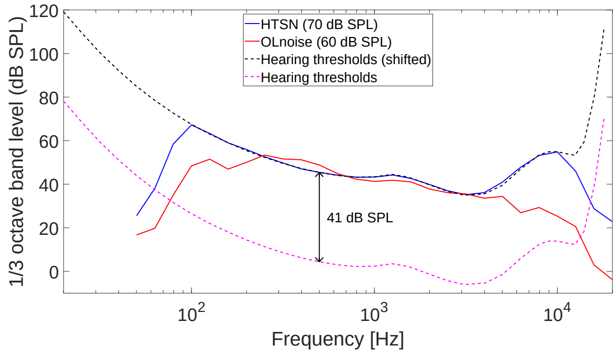

Figure 1: Hearing threshold according to ISO 389-7 (pink) [10], the shifted hearing threshold (black), and the one-third octave band analysis (dB) of the interference signals HTSN (blue) and OLnoise (red) as a function of frequency.

II.V. Procedure

Firstly the listening effort was assessed using ACALES, then the SRT20, SRT50, and SRT80 were determined using the adaptive OLSA procedure (see Chapter II.II). Measurements included two conditions: OLnoise and HTSN. Each participant completed the ACALES test for both conditions in alternating order. To minimise training effects in the OLSA, two training lists (20 sentences each) were conducted at SRT50, one per noise signal, before the actual measurements. The six measurements (three per condition) were randomized using a Latin square to reduce order effects.

II.VI. Data processing and statistical method

Data from the OLSA and ACALES measurements, collected via OMA, were processed and analyzed in MATLAB (Version R2024b). Logistic psychometric functions and ACALES curves were fitted to examine the relationship between speech intelligibility and listening effort, identifying the speech intelligibility level with the highest effort. Psychometric function slopes were calculated for each participant. Normality was assessed using the Shapiro-Wilk test. Differences between signals were analyzed with paired t-tests and Wilcoxon signed-rank tests.

III. Results and discussion

III.I. ACALES and OLSA data

The data from the OLSA measurements are summarized in Table 1. The SRT50 of the OLnoise (-7.2 ± 0.6 dB SNR) agrees well with literature values (-7.1 ± 1.1 dB SNR, [8]). In comparison, the HTSN shows greater variability, especially at SRT80. The SRT values of the two signals differ by about 10 dB SNR for all three SRTs. The slope of the psychometric function was calculated in two ways: individually for each subject and signal, yielding 18 ± 4.4 %/dB, and based on averaged SRT values, resulting in 17.2 %/dB for the OLnoise. The literature value for OLnoise of 17.1 %/dB was confirmed [8]. For HTSN, the individual slope was 16 ± 5.2 %/dB, while the averaged value was 14.9 %/dB, indicating a flatter slope than OLnoise but steeper than the literature value of 11.3 %/dB slope in quiet (monaural presentation) [8]. The 18 individually calculated slopes were tested for normal distribution (Shapiro-Wilk test), with no normal distribution found ($p<0.05$). The Wilcoxon signed-rank test revealed no significant difference ($p=0.15$). The ACALES results in

Table 1: Means, standard deviations and differences in SRT values for HTSN and OLnoise.

SRT	Mean HTSN	Std HTSN	Mean OLnoise	Std OLnoise	Difference (OLnoise - HTSN)
20	-19.3 dB	1.0 dB	-8.7 dB	0.7 dB	10.5 dB
50	-17.5 dB	0.8 dB	-7.2 dB	0.6 dB	10.2 dB
80	-15.2 dB	1.3 dB	-5.2 dB	0.7 dB	10.0 dB

Table 2 are similar to those in Table 1, with ESCU 1, 7, and 13 listed instead of the three SRTs. The OLnoise values are 3.8 dB for ESCU 1 and -6.6 dB for ESCU 13. While the ESCU 1 value deviates from literature data (9.5 dB), the ESCU 13 value (-8 dB) agrees well with the literature [4]. One possible reason for this deviation may be the different fixed interference levels used in the two experiments (see Chapter II.III). Comparison between HTSN and OLnoise shows that the difference in SNR increases as ESCU increases (ESCU 1: 6.5 dB, ESCU 13: 9.6 dB). For HTSN, the values are -2.7 dB for ESCU 1 and -16.2 dB for ESCU 13. Tests for normal distribution (Shapiro-Wilk test) showed that in ESCU 1, both groups were normally distributed ($p>0.05$), allowing a paired t-test, which found a highly significant difference ($p<0.0001$). In ESCU 13, only the HTSN group was normally distributed ($p>0.05$), so a Wilcoxon signed-rank test was used, revealing a significant difference ($p<0.0002$). These results highlight significant differences between signal types at both ESCU levels, emphasizing the impact of noise type on SNR. Fig. 2 shows the mean as well as

Table 2: Means, standard deviations and differences in ESCU values for HTSN and OLnoise.

ESCU	Mean HTSN	Std HTSN	Mean OLnoise	Std OLnoise	Difference (OLnoise - HTSN)
1	-2.7 dB	3.0 dB	3.8 dB	3.8 dB	6.5 dB
7	-9.5 dB	2.8 dB	-1.7 dB	2.3 dB	7.7 dB
13	-16.2 dB	2.4 dB	-6.6 dB	3.0 dB	9.6 dB

the individual results of the two signals. Fig. 2 presents both individual and mean results for the two signals. Averaged psychometric functions and ACALES curves are shown for HTSN (blue) and OLnoise (red), with individual curves displayed in lighter shades of the respective colors. As already described in the analysis for OLSA and ACALES, the curves of the two signals show a clear shift.

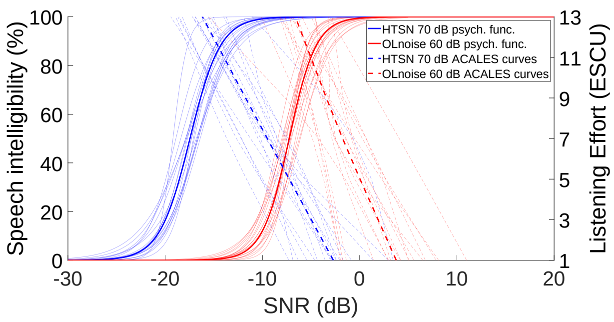

Figure 2: Psychometric functions (solid) and ACALES curves (dashed) for HTSN (blue) and OLnoise (red), with individual data in lighter shades, illustrating speech intelligibility (%) and listening effort (ESCU) as a function of SNR (dB).

III.II. Listening effort and speech intelligibility

Fig. 3 shows the psychometric functions (dashed lines) and ACALES curves (dotted lines) for HTSN (blue), OLnoise (red), and quiet (black), with vertical lines indicating ESCU 13 to the respective psychometric functions (solid lines). Speech intelligibility (left y-axis) and ESCUs (right y-axis) are plotted against shifted speech levels (dB), with psychometric functions aligned to the SRT50 at 0 dB. The ACALES curves were adjusted accordingly. The HTSN psychometric function is flatter than OLnoise but steeper than the psychometric function in quiet. Similarly, the HTSN ACALES curve is less steep than OLnoise but much steeper than the quiet curve. The difference in slope between OLnoise and HTSN can be partly explained by their spectral characteristics: HTSN aligns with the hearing threshold of young normal-hearing adults, while OLnoise matches the speech material used in OLSA and ACALES measurements. The highest listening effort (ESCU 13) occurred with HTSN at 78 % speech intelligibility, compared to 67 % with OLnoise. In quiet, the value was 92 % [6], meaning the HTSN is 14 % below and 11 % above the OLnoise value. These results position HTSN between quiet and OLnoise values, suggesting that while HTSN shares some traits with quiet, cognitive factors beyond the masking effect of the ear may also be involved.

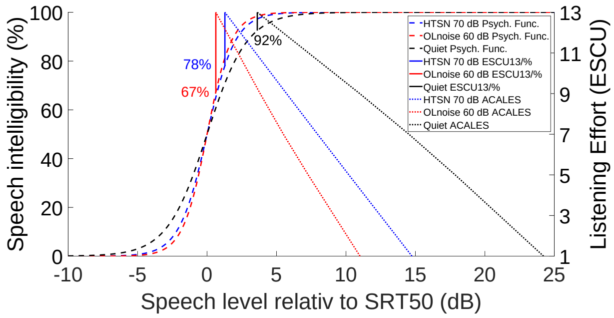

Figure 3: Psychometric functions (dashed) and ACALES curves (dotted) for HTSN (blue), OLnoise (red), and quiet (black) [6], with vertical lines (solid) indicating speech intelligibility at ESCU 13. Speech intelligibility (%) and listening effort (ESCU) are shown as a function of speech level relativ to SRT50 (dB).

IV. Conclusion

The results of this study indicate that the unmatched noise, HTSN, lies between OLnoise and quiet in terms of the steepness of the psychometric functions and ACALES curves. The highest listening effort (ESCU 13) was observed for HTSN at 78 % speech intelligibility, which is higher than OLnoise (67 %) but considerably lower than quiet (92 %). These results suggest that HTSN shares some characteristics with quiet but does not fully replicate it. Future studies should explore cognitive factors beyond internal noise masking in HTSN that may affect speech intelligibility and listening effort in quiet.

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Author's statement

Conflict of interest: Authors state no conflict of interest. DeepL and ChatGPT were used for the linguistic fine-tuning of this work. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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