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# Hearing-aid settings in connection to supra-threshold auditory processing deficits

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Plomp (1986) described the consequences of hearing impairment in speech communication as the sum of two components: attenuation and distortion. Recent studies have shown that the sensitivity to spectro-temporal modulations (STM) might be linked to speech intelligibility in noise, suggesting that supra-threshold, or "internal", distortions would affect both speech and STM perception similarly. Furthermore, reduced sensitivity to STM may also affect a listener's preference for a hearing aid (HA) compensation strategy. Here, speech intelligibility and STM sensitivity were measured in 20 hearing-impaired (HI) listeners. One group of the listeners (Group A) showed an inability to detect STM, whereas the other listeners (Group B) exhibited similar thresholds as the control group with young normal-hearing (NH) listeners. The two HI groups participated in a perceptual evaluation experiment using multi-stimulus comparisons (MUSHRA). The audio files were processed by a HA simulator fitted to the individual hearing loss and the performance was rated in terms of four attributes: clarity, comfort, preference and listening effort. A correlation analysis showed that clarity and preference were correlated in Group A whereas comfort and listening effort were correlated in Group B. The classification of HI listeners in auditory profiles might be valuable for efficient HA fitting.

## INTRODUCTION

Plomp (1986) proposed a model based on observations of speech-in-noise intelligibility tests. The model describes the consequences of hearing loss (HL) in speech communication as the sum of two components: attenuation and distortion. According to the model, listeners with only an attenuation component exhibit elevated speech reception thresholds (SRT) in quiet but their performance in speech-in-noise tests is comparable to the one of a normal-hearing listener. In contrast, listeners with a distortion component show elevated SRTs both in quiet and in noise. The SRT model of Plomp constitutes a scientifically founded way for quantifying the effects of hearing impairment beyond the audiogram (Soli and Wong, 2008). The model relies on restrictive assumptions related to the test procedure (Plomp, 1986), which makes the comparison of results across different studies difficult, especially when

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using other speech materials, spatial configurations or noise types. Therefore, other auditory tests, able to indicate whether a distortion component is present, would be of interest for a further hearing loss characterization. Several studies have aimed to characterize the distortion component by studying the relationship between different aspects of auditory processing, such as frequency selectivity and temporal processing, and speech intelligibility (Houtgast and Festen , 2008). However, none of the studied auditory processing deficits could fully account for the degraded speech perception results.

Hearing aid (HA) fitting is commonly based on applying a frequency-dependent non-linear amplification based on the pure-tone audiogram. Current hearing-aid technology allows advanced signal processing that can improve the signal-to-noise ratio (SNR) of the acoustic input signals presented to the ears. The advanced features are usually activated on-demand and not adjusted to the individual needs. The personalization of the HA settings, based on outcome measures that reflect supra-threshold auditory processing deficits, may therefore improve the individual listener's satisfaction. Here, two types of noise management strategies were evaluated by means of subjective assessments. It is hypothesized that listeners with a high degree of supra-threshold deficits would indicate a preference for more aggressive noise reduction.

The mammalian primary auditory cortex encodes dynamic signals by performing a spectro-temporal decomposition of the neural response (Kowalski *et al.*, 1996). The analysis of spectro-temporally modulated signals by the auditory system might be crucial for the discrimination of complex sounds, such as speech. Mehraei *et al.* (2014) investigated the spectro-temporal modulation (STM) sensitivity in normal-hearing (NH) and hearing-impaired (HI) listeners and its relation to speech intelligibility in noise. Results using one-octave wide carriers showed a significant difference between NH and HI listeners for some specific combinations of spectral and temporal modulations. These conditions, combined with the individual audibility predicted by the speech intelligibility index (SII; ANSI S3.5-1997), were able to account for 89% of the variance in the data. The main hypothesis of the present study was that a reduced STM sensitivity is associated with supra-threshold auditory processing deficits, which cause distortions in the internal representation of the acoustic stimuli, such that listeners with a reduced STM sensitivity would exhibit a distortion component that causes elevated speech reception thresholds in noise.

The goal of the present study was to explore the viability of a classification of the HI listeners based on their supra-threshold deficits by means of a simple STM test. The listeners were divided into two groups based on their STM sensitivity: Group A, with a reduced STM sensitivity; and Group B, with a fairly high STM sensitivity. This classification was used to explore the differences between both groups in terms of speech intelligibility and preference for hearing-aid processing. It is hypothesized that Group A would show a poorer speech-in-noise discrimination and a preference for more aggressive settings in a HA noise management algorithm, whereas Group B would show near-normal speech-in-noise intelligibility.

## METHOD

Twenty-six subjects participated in this study, divided into a control group (NH) and a HI group with different degrees of sensorineural hearing loss. The NH group consisted of five listeners (1 female) aged between 22 and 58 (median 24) years. Their audiograms did not show any threshold above 20 dB hearing level (HL), and no air-bone gaps were observed. The age of the HI group (20 listeners) ranged between 26 and 86 years (median 69, 12 females). The listeners were divided into two groups. The criterion for placing subjects in one of the two groups was chosen to be at -3 dB STM sensitivity in the listeners' better ear. This criterion was based on the results from Bernstein *et al.* (2016), where the average STM sensitivity was found to approximately -3 dB. The audiometry was performed following the standard ISO 8253-1:2010 and using a two-channel audiometer Interacoustics AA222 and Sennheiser HDA200 headphones. At least one ear of each subject was explored by the whole test battery.

### Experimental set-up

All tests were carried out with the same equipment. For the behavioural tests, the stimuli were generated in MATLAB at a sampling frequency of 44.1 kHz and converted in analogue signals by a sound card (RME Fireface). The software Senselab Online 3.1.6 was used for the subjective assessments. The signals were amplified (RME QuadMic) in the analogue domain and presented to the listener through Etymotic research ER-2 insertion earphones with foam ear tips. The tests were performed in a double-walled sound-attenuating booth.

### Behavioural tests

Speech reception thresholds were measured using the Danish hearing-in-noise test (HINT; Nielsen and Dau, 2011). The SRT was measured in quiet ($SRT_Q$) and in speech-shaped stationary noise ($SRT_N$). The level of the noise was set at $SRT_Q + 30$ dB. For convenience, Lists 1 and 3 were always used for $SRT_Q$, and Lists 7 and 8 were used for the $SRT_N$ measurements. The $SRT_Q$ was defined as the speech level, in dB sound pressure level (SPL), at which 50% of the sentences are correctly recognized. The $SRT_N$ was defined in terms of SNR. The adaptive procedure for the speech-in-noise test, as described in Nielsen and Dau (2011), was used for estimating SRT.

One-octave wide moving-ripple stimuli were generated in a similar way as in Mehraei *et al.* (2014). Two STM conditions were found to be the most significant predictors of speech-in-noise performance in Mehraei *et al.* (2014). However, only the condition with the ripple centered at $f_c = 1000$ Hz, a spectral density of $\Omega = 2c/o$, and an amplitude modulation frequency of $f_m = 4$ Hz was considered. The stimuli were generated in the frequency domain as the sum of 32 equal-amplitude carrier tones per octave band, logarithmically spaced. All carriers were presented in random phase. Sinusoidal amplitude modulation was applied to the carriers by additional side-bands with instantaneous phases increasing according to the frequency space. Unmodulated

carriers, presented at 15 dB below the level of the modulated band, served to control for off-frequency listening. The stimuli in the STM detection task were presented at the same level as the speech signal at $SRT_N$. The subjects' task was to detect which interval contained the STM stimulus in a 3-interval 3-AFC paradigm. In the initial trial, the target signal was fully modulated whereas the other two intervals were unmodulated. A three-down one-up tracking procedure approximated the 79.4% point of the psychometric function. The modulation depth in dB [20log(m)] was decreased in steps of 6 dB until the first reversal. The step-size was then decreased to 4 dB for the next two reversals. The threshold was estimated as the mean of six additional reversals with the final step size of 2 dB. Two repetitions were obtained for each ear. All signals were 500 ms long, including 5 ms raised-cosine ramps, separated by 500 ms silence.

### Subjective assessment

The subjective assessment was based on a multi-stimulus comparison paradigm (ITU-R.BS.1534-1, 2001) combined with a HA simulator. The hearing-aid simulator consisted of an 18-channel wide-dynamic-range compressor (WDRC) followed by a noise-management algorithm based on a speech intelligibility index (SII) optimizer (Kuk and Paludan, 2006), referred to here as the "speech enhancer" (SE). Individual gain, following the NAL-NL2 prescription, was applied before the noise management algorithm. Two settings of the SE were evaluated: $SE1^{0}_{-12}$ (aggressive noise reduction) where the gain in each frequency band was reduced in a range from 0 to -12 dB to optimize the speech intelligibility of the input signal according to SII; and $SE2^{+6}_{-6}$ (less aggressive noise reduction) where the gain could be increased or reduced in a range from -6 dB to 6 dB to optimize SII. Although the two settings aimed for improved speech intelligibility, the additional gain provided by SE2 may affect listening comfort (Kuk and Paludan, 2006). The noise management algorithm analyzed the long-term signal and applied the gain reduction over the whole sound sample.

The multi-comparison test was implemented in SenseLab Online 3.1.6 (SenseLab, 2015). Five HA settings were presented in each run, including a reference (+6 dB SNR), a hidden anchor (-6 dB SNR) and a control (noise-management OFF). The evaluation was performed in three challenging noisy environments (café, party and traffic) and two SNR conditions, a difficult condition (+1 dB SNR) and a more favourable (+4 dB SNR). The target signal was running speech taken from an audiobook. Four attributes were considered: clarity (contrast between the speech signal and the noise), comfort (comfortability of the whole sound scene), listening effort (difficulties to understand the speech target signal) and preference.

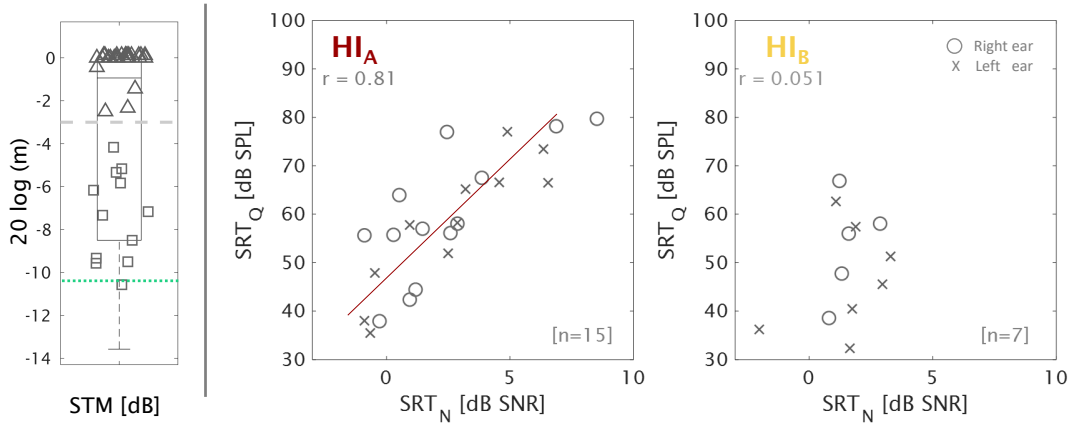


**Fig. 1:** Results of the behavioural tests. Left: Spectro-temporal modulation detection. The grey dashed line corresponds to -3 dB and the green dotted line corresponds to the averaged results of the NH group. Right: Speech intelligibility tests in quiet and noise for the two HI groups. The origin of coordinates corresponds to the averaged thresholds of the NH listeners.

## RESULTS

Figure 1 (left) shows the STM sensitivity results of Group A, indicated as (△), and of Group B, indicated as (□). In Group A, eight listeners were not able to perform the test, reporting that there was no difference between the unmodulated and the STM stimuli. The middle and right panels of Fig. 1 show the results of the speech intelligibility tests. $SRT_Q$ is shown as a function of $SRT_N$. Group A (middle panel) showed a correlation between $SRT_Q$ and $SRT_N$ whereas for Group B (right panel) $SRT_N$ was not correlated to $SRT_Q$. Group B's $SRT_N$ values were slightly higher than the SRT values expected for NH listeners (-2 dB SNR).

Figure 2 shows the overall averaged results of the subjective ratings and for the noise types and SNR conditions. Results are shown separately for Group A (top) and Group B (bottom). The ratings of both groups were within a small range between 35 and 65 %. Group A disliked SE2 ($< 40\%$), which provided less comfort ($< 35\%$) and higher listening effort ($> 60\%$), but this group was indifferent in terms of clarity. Group B prefered SE2 ($> 45\%$), which provided more clarity ($> 50\%$) and less listening effort ($< 50\%$) but also less comfort ($< 45\%$). Even though the results were highly correlated across the four attributes, Group A's preference was more significantly correlated† with comfort ($r = 0.49$) than with clarity ($r = 0.39$). In contrast, for Group B, preference and listening effort were more significantly correlated with clarity ($r = 0.40$) than with comfort ($r = 0.37$).

†Spearman's correlation

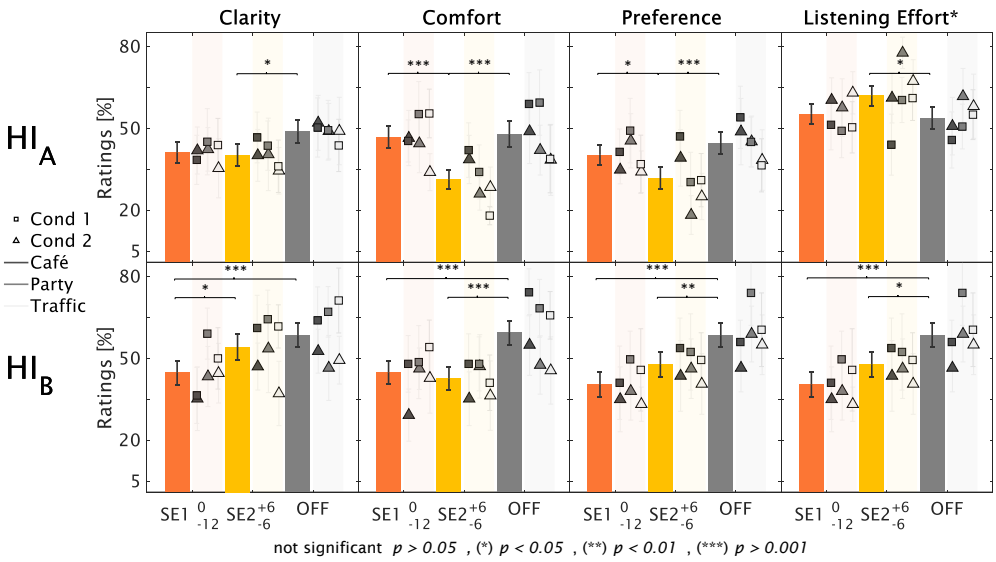


**Fig. 2:** HA evaluation. Mean and confidence intervals of the ratings of the 4 attributes for the three HA settings. Results of overall Group data (bars) as well as divided by noisy environments and SNR conditions together with 95% confidence intervals. Only seven listeners from each group participated in the subjective assessments

The overall data of the subjective assessments were analyzed using a mixed-linear model that includes the main fixed effects and first-order interactions. The results of the analysis of variance (ANOVA) revealed that (i) the noise type only affected listening comfort ($F(2,800) = 0.7;\ p < 0.001$); (ii) the SNR affected listening effort ($F(1,787) = 11.2;\ p < 0.001$); and (iii) the interaction between HA settings and HI group was significant for all attributes. The higher influence of this interaction was found for preference ($F(4,800) = 6.6;\ p < 0.001$) and the lowest for listening effort ($F(4,787) = 4.5;\ p < 0.01$). The results of the statistical analysis showed only a significant difference between the groups in the ratings of less aggressive setting (SE2) which was preferred by Group B.

## DISCUSSION

The participants were divided into two groups based on their performance in the STM sensitivity test. The overall results spanned between -10 and 0 dB and eight listeners were not able to perform the test. This was in line with Bernstein *et al.* (2016), where a substantial number of subjects was not able to perform a similar test and had to be tested with a different test paradigm. Zaar *et al.* (2020) tested 30 HI listeners with similar stimuli as in Bernstein *et al.* (2016) but with an individual hearing-loss compensation that ensures that the presentation level was at 15 dB sensation level (SL) or above. Additionally, the stimuli used in Zaar *et al.* (2020) were slightly longer (1

s). In their study, the STM detection thresholds were between -15 and -5 dB and all listeners were able to perform the test. Furthermore, their results of aided speech-in-noise intelligibility were significantly correlated with the aided STM performance. The frequency-selective amplification and the duration of the stimuli might have made the cues provided by the STM stimulus more salient. In the present study, the goal was to separate the listeners into two groups, associated with different degrees of supra-threshold deficits. Therefore, STM stimuli, such that some listeners are not able to perform the test, might be more sensitive for that purpose.

Plomp argued that the distortion component affects both speech intelligibility in quiet and noise, whereas the attenuation component of the hearing loss only affects speech in quiet and does not yield elevated SRT in noise. In the present study, the group of listeners with lower STM sensitivity (Group A) showed elevated $SRT_Q$ and $SRT_N$. In this group, the results obtained for speech intelligibility in quiet and in noise were highly correlated to each other. In contrast, in Group B, the speech intelligibility results (in quiet and in noise) were not correlated, suggesting that $SRT_Q$, in this case, might have only been affected by the attenuation component. Despite the fact that $SRT_N$ values of Group B were slightly elevated compared to the $SRT_N$ values of NH listeners, Group A is more likely to reflect supra-threshold distortions than Group B.

Both groups preferred SE OFF over the two evaluated algorithms. The reason for this could be that the signals were not adjusted in terms of loudness after noise management. Besides, the frequency responses of the reference (+6dB SNR condition) and the SE OFF setting were identical. This might have influenced the judgments of the participants by rating SE OFF higher because of its similarity with the reference. In the group with reduced STM sensitivity (Group A), there was not a significant preference for aggressive noise reduction compared to the SE OFF setting. However, the listeners of Group A preferred the aggressive noise reduction over the speech enhancer with additional gain. Zaar *et al.* (2020) evaluated the benefit of different parameters of a noise-reduction algorithm by means of speech intelligibility and listening effort, as well as the subjective preference in a field study with hearing aids. STM sensitivity was correlated with a preference for noise-reduction settings (i.e., listeners with poorer STM sensitivity preferred more aggressive noise reduction). Thus, in both studies, the adjustment of noise-management algorithms based on the STM sensitivity showed potential for an individualized HA fitting.

## CONCLUSION

STM sensitivity can be connected to speech-in-noise intelligibility and hearing-aid fitting strategies. Listeners with a low STM sensitivity (i.e. higher thresholds) seemed to prefer more aggressive noise reduction and higher listening comfort, whereas listeners with high STM sensitivity preferred additional gain that may have improved speech clarity. The individualization of HA parameters based on listeners' supra-threshold hearing abilities might increase HA users' satisfaction.

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