processing can significantly assist HI listeners to communicate more effectively in the kind of complex listening situations examined in this study.

We wish to acknowledge the invaluable support provided by Elizabeth Convery and Els Walravens from the National Acoustic Laboratories in recruiting and conducting the trials for this study.

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Perceptual comparison of noise reduction in hearing aids

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Knowledge on perceptual consequences of single-microphone noise reduction in hearing aids is limited. We developed and evaluated a filtering method that allowed us to directly compare noise reduction systems from different hearing aids. Using this method, we compared noise reduction from four different hearing aids in a paired-comparisons design. Preference strength of our normal hearing subjects appeared to differ between noise reduction systems as well as between SNRs. Both factors are relevant for the interpretation of previous noise-reduction studies as well as for hearing-aid selection and fine-tuning.

INTRODUCTION

Most modern hearing aids use single-microphone noise reduction to increase listening comfort in noisy environments. Unfortunately, details about the properties of noise reduction in hearing aids are rarely provided. Furthermore, there is limited knowledge about possible benefits of noise reduction. Some studies reported a clear preference of listeners for noise reduction *on* over *off* (Boymans and Dreschler 2000; Ricketts and Hornsby 2005). However, other studies could not confirm such positive effects (Alcantara *et al*. 2003; Bentler *et al*. 2008). Each study compared noise reduction on and off *within* one type of hearing aid. Differences in noise reduction *between* hearing aids may therefore contribute to the diverging results. Thus, there is a need for a method to directly compare different hearing-aid noise-reduction systems to each other, without the dominating effects of other hearing-aid characteristics (e.g. frequency-dependent gain). This led to our first research question:

1. Can we remove the perceptual differences between recordings from different hearing aids, so that they are perceptually equal if noise reduction is turned off?

We designed and evaluated a filter method to remove the perceptual differences. This was described in detail in Houben *et al*. (2011) and summarized here as Experiment 1. The method allowed us to do a paired-comparisons experiment (Experiment 2) in order to answer the following question:

2. Do normal hearing subjects have preference for
   - (a) noise reduction *on* over noise reduction *off within* a hearing aid?
   - (b) noise reduction from one hearing aid over noise reduction from another?

Proceedings of ISAAR 2011: Speech perception and auditory disorders. 3rd International Symposium on Auditory and Audiological Research. August 2011, Nyborg, Denmark. Edited by T. Dau, M. L. Jepsen, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN 87-990013-3-0. EAN 9788799001330. The Danavox Jubilee Foundation, 2012.

EXPERIMENT 1

Methods

Hearing aids

We selected five frequently used behind-the-ear hearing aids from different brands (Oticon, Phonak, ReSound, Starkey and Widex). This selection was a representative sample of the commercial hearing aids on the market at the start of the experiments. We turned off all signal processing features in the hearing aids (directionality, feedback control, noise reduction, compression, frequency transposition, etc.) and carefully adjusted their gain to obtain a linear response and the same insertion gain for all hearing aids.

Recording setup

All recordings and experimental validations took place in a sound-treated double-walled booth. We recorded the hearing-aid output with the use of a B&K Head and Torso Simulator (HATS Type 4128C) fitted with a custom made tight-fitting ear mould without venting. All hearing-aid input signals were presented by a near-field monitoring speaker placed in front of the hearing-aid microphone (on axis). All input signals were corrected for the speaker response.

Filter design

In spite of the careful hearing-aid gain adjustment, there remained small differences in frequency response between hearing aids (see Figure 1, upper panel). To correct for these differences, we designed an inverse filter for each hearing aid. We compared the hearing-aid output to the output of a reference to obtain the required filter response. We used the Matlab function "fir2" to calculate the filter coefficients (500 taps) based on the required response. Additionally the frequency response was limited to 100 Hz through 5.8 kHz with elliptical filters of the 7th order.

Subjects

To test whether listeners could distinguish between the hearing-aid recordings, we designed a detection experiment. Six normal hearing subjects aged between 24 and 37 years (average = 28.3 years) participated in this study. Their hearing thresholds were 20 dB hearing level or better at 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz. We chose normal-hearing listeners because they are assumingly better at detecting differences between stimuli than hearing impaired listeners. If differences cannot be detected by normal-hearing subjects, we can be quite confident that these differences will also be unnoticeable for hearing-impaired subjects.

Stimuli

We recorded the hearing aid output for speech (Versfeld *et al*. 2000) in speech babble (Luts *et al*., 2010) at a signal to noise ratio of +10 dB(A). All hearing-aid signal processing features (including noise reduction) were turned off. We did the subjective evaluation for two sets of stimuli. The first set consisted of the hearing-aid recordings with band-pass limitation between 100 Hz and 5.8 kHz ("band-pass filtered"). The second set had the same band-pass limitation, but was additionally filtered with the inverse filter that was designed for each hearing aid ("fully filtered").

Detection task

Subjects listened to three stimuli of which two were recordings from the same hearing aid (standard) and one from another aid (target). The subjects' task was to select the hearing-aid recording that differed from the other two (i.e. an odd-ball paradigm). Recordings from each of the five hearing aids were used as target with standards of the recordings of all other hearing aids and vice versa. This resulted in 20 stimulus pairs (5*4, including AAB BBA) and each stimulus pair was tested 3 times, leading to 60 trials per filter condition (band-pass filtered or fully filtered) and thus 120 trials per subject. The stimuli were presented diotically with Sennheiser HDA200 headphones at 70 dB(A). Directly after the subjects had given their response, they received feedback on whether they had chosen the correct stimulus and if not, which one they should have chosen.

Results

Figure 1 shows the spectra of pink noise recorded by the five hearing aids. The upper panel shows the spectra prior to filtering and the lower panel post filtering. The filtering removed the differences in frequency response between hearing aids.

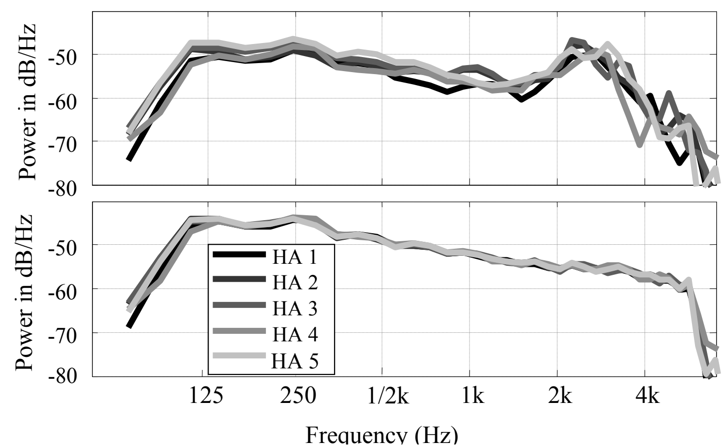

Fig. 1: Frequency response of the hearing-aid output for an input of pink noise at 70 dB SPL. Top panel: spectra of the raw recordings of the five hearing aids. Bottom panel: spectra of the recordings after inverse filtering.

Figure 2 shows the percentages of correct detection averaged over all subjects. The average detection score was 87% for the band-pass filtered signals and 39% for the fully filtered signals. A two-way analysis of variance with subject as random effect and hearing aid and stimulus set as fixed effects indicated a significant effect of stimulus set ($F(1,20)=90$, $p<0.0005$) and a significant interaction between subject and filter type ($F(5,20)=6$, $p<0.005$).

One-sided t-tests with Bonferroni correction showed that all detection rates for the band-pass filtered stimuli were significantly higher than chance level ($p>0.13$). For the fully filtered stimuli, however, none of the detection rates deviated significantly from chance level ($p\leq0.001$).

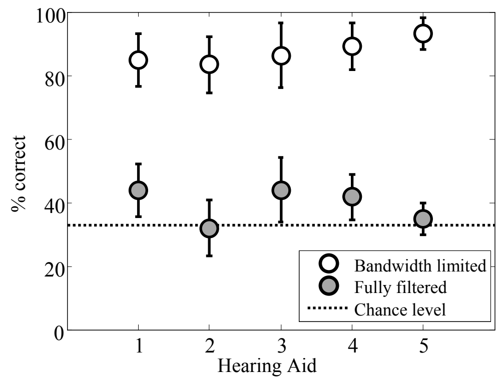

Fig. 2: Percentage of times the subject correctly detected each hearing aid as deviant from the other stimuli. Error bars denote 95% confidence intervals. (the order of the hearing aids has been randomized)

Discussion

The results show that it is possible to remove the perceptual differences between recordings from different hearing aids. Normal hearing subjects could not distinguish between recordings of different hearing aids with noise reduction off.

The high detection rates for the band-pass filtered stimuli show that it was not sufficient to carefully adjust the hearing-aid gain and limit the bandwidth of the recordings. However, the fact that detection rates for the fully filtered condition did not deviate significantly from chance level, confirms that an additional inverse filter for each hearing aid was able to remove the remaining perceptual differences.

Once an inverse filter is designed for a specific linearly fitted hearing aid, it can also be applied on recordings from the same hearing aid with noise reduction turned on. The only difference between hearing aids is then caused by the noise reduction, because all hearing aids are perceptually equal when noise reduction was turned off. This allows for direct comparison of noise reduction from different hearing aids without the confounding effect of other hearing-aid characteristics. This will be used in Experiment 2.

EXPERIMENT 2

Methods

Subjects

Ten normal hearing subjects aged between 19 and 23 years (average = 20.8 years) participated in this study. These subjects had not participated in Experiment 1. Their hearing thresholds were 15 dB hearing level or better at 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz. Again, we chose normal-hearing subjects because of their ability to detect differences between signals well. Furthermore, the choice for normal hearing subjects allows us to compare noise reduction systems without the interaction with dynamic range compression.

Hearing aids

We used four hearing aids from Experiment 1. All settings were identical to those used in Experiment 1 and we could therefore use the previously built inverse filters. Now, we recorded the reference condition with noise reduction turned off for one hearing aid. This recording, the “unprocessed” condition, represented all hearing aids without noise reduction. Next we recorded all hearing aids with noise reduction set to the maximum. The recordings were filtered with the hearing-aid specific inverse filter. This gave four different noise reduction conditions, coded as NR1 through NR4 (again in random order).

Stimuli

We recorded the hearing-aid output for Dutch female speech (Versfeld *et al*. 2000) in a multitalker babble noise (Luts *et al*. 2010). The signals were presented to each hearing aid with a noise level of 70 dB(A) and two different speech levels (66 and 74 dB(A)) to form speech in noise at signal to noise ratios (SNRs) of -4 and +4 dB. The noise was continuous, while the speech paused one second between sentences. One list of 36 seconds preceded the stimulus lists in each condition to allow the hearing aid to adapt to the input signals.

Stimuli consisted of single sentences with 0.5 second of noise before and after the sentence. The stimuli were presented diotically with Sennheiser HDA200 headphones. The noise level was 70 dB(A) for all stimuli in the *unprocessed* condition.

Paired comparison rating

We used paired comparison rating (a two-interval, seven-alternative forced choice paradigm) to determine the preference of subjects. Subjects listened to two fragments A and B, and were asked which one they would prefer for prolonged listening. They could choose from seven possible answers, ranging from “A is much better” to “B is much better”. Subjects had the possibility to indicate no difference between A and B. Subjects were allowed to listen to the fragments as often as they preferred before they made their choice.

All five conditions were paired with all others, resulting in ten different stimulus pairs. Three runs of ten comparisons were done both at -4 and +4 dB SNR, resulting in a total of 60 comparisons per subject. All subjects started with four training pairs. Subsequently, five subjects started with all comparisons at -4 dB SNR, the other five started at +4 dB SNR.

Results

For the analysis of the paired comparison rating data we used the log-linear modelling approach for ordinal paired-comparisons described by Dittrich *et al*. (2004). The model is a log-linear representation of the Bradley-Terry model (Bradley and Terry 1952) and is extended for paired comparison data with multiple response categories, including a "no difference" option. By fitting this model to the paired comparison data, we obtained estimates of the so called "worth" parameters, describing the location of the five processing conditions on the subject's preference scale. This scale can be interpreted as a ratio scale, thus providing information about the ranking of preference for the five conditions as well as the strength of preference. A model was fitted for each individual run of ten comparisons, resulting in three models per subject per SNR. We tested the goodness-of-fit for all models by comparing the obtained model with a saturated model (a model reproducing the data perfectly). All p-values were >0.95, indicating a high agreement with the saturated model and all models thus could be accepted.

Figure 3 shows the worth estimates for each processing condition averaged over all subjects. The data were plotted relative to the unprocessed condition. Error bars show the 95% confidence interval between subjects. Because we calculated the data relative to unprocessed for each subject, the error bars for the unprocessed condition are zero.

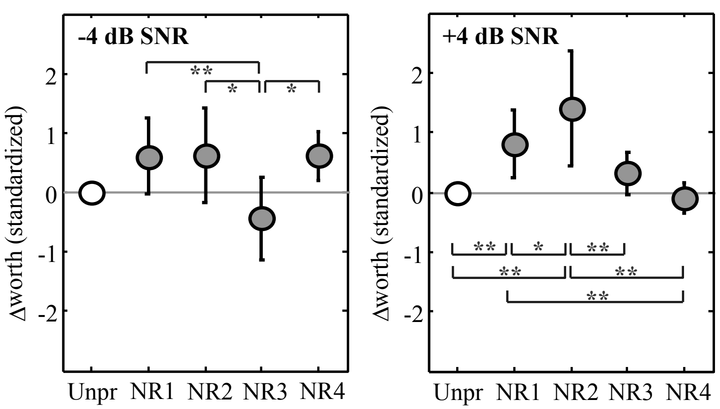

Fig. 3: Estimated worth for the preference averaged over the 10 subjects. Data were standardized and then plotted relative to unprocessed. Error bars show the 95% confidence interval between subjects. Higher values mean stronger preference. Horizontal bars indicate which processing conditions differ significantly from each other (* p< 0.05; ** p <0.001, after Bonferroni correction for 10 comparisons).

We did a repeated measures ANOVA on the estimated worth values with SNR and processing condition as fixed effects and subject as random effect. We found a significant effect of processing condition (F(4,36)=5.6, p=0.001) and significant interactions between processing condition and SNR (F(4,263)=8.8, p<0.001), between processing condition and subject (F(36,263)=3.3, p<0.001) and between SNR and subject (F(9,263)>7.6, p<0.001). Because of the significant interaction between processing condition and SNR, we did subsequent post-hoc pairwise comparisons between processing conditions separately for both SNRs. The horizontal lines in Figure 3 indicate which conditions differed significantly from each other after Bonferroni correction for 10 comparisons.

Discussion

Our results show that normal hearing subjects prefer noise reduction *on* over *off* for two of the four selected hearing aids at +4 dB SNR. The hearing aid noise reductions are not all equal; subjects prefer some systems over others.

The strength of preference as well as the ranking of the different conditions differed between SNRs. None of the noise reduction systems was preferred over no noise reduction at -4 dB SNR. Possibly, it was harder for the noise reduction to differentiate well between speech and noise at this SNR, so that not only the noise was reduced, but also the speech might have been affected.

Our results support interpretation of the diverging results from previous studies. First, we found that noise reduction *on* was not preferred in all hearing aids over noise reduction *off*. Secondly, significant preferences for noise reduction *on* over *off* were only found at +4 dB SNR and not at -4 dB SNR. Although there are many other factors that play a role (for instance the type of noise and other hearing aid characteristics) we conclude that the use of different hearing aids as well as different SNRs for the stimuli may have contributed to the seemingly conflicting results of previous studies on the perceptual effects of noise reduction.

Of course, our preference results are not meant to draw conclusions on which hearing aid would be better for daily use. Our approach is required as a first exploring step to learn more about the perceptual effects of noise reduction. Subsequent research need to investigate the effect of noise reduction in the context of the hearing aid, thus with other processing features enabled.

The preferences of our normal-hearing subjects might be representative also for listeners with a conductive hearing loss. However, for listeners with a sensorineural hearing loss it becomes more complicated because hearing aids usually apply dynamic range compression for this type of hearing loss. The interactions of noise reduction with compression are as yet studied only occasionally (Chung 2007, Anderson 2009) and demand for more exhaustive investigations.

CONCLUSION

We conclude from Experiment 1 that our combination of an inverse filter and band-pass filter offers the opportunity to directly compare hearing-aid noise reduction systems. This made that Experiment 2 was, as far as we know, the first in which noise reduction systems from different hearing aids were directly compared to each other. We conclude from the results that it depends on the type of noise reduction as well as the SNR whether normal hearing subjects prefer noise reduction over no noise reduction or over other types of noise reduction. These findings support the interpretation of previous studies on noise reduction. Furthermore, the results imply that it might be useful to give hearing-aid users the possibility to compare different noise-reduction systems in the process of selecting the most appropriate hearing aid and of fine-tuning for the optimal setting.

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Psychosocial factors affecting hearing aid adjustment

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This presentation outlines the answers from a questionnaire sent out to more than 800 users with hearing aids dispensed from public clinics in Denmark in the autumn of 2010. Answers indicate a generally high satisfaction and usage time with the dispensed hearing aids, and that this satisfaction, as expected, correlates with factors related to especially expectation, motivation, personal skills of the fitter, and user friendliness of the hearing instrument. All in all the answers from this quite large population offers a quantitative insight into the non technical factors that also affects hearing aid fitting.

BACKGROUND

Hearing aid satisfaction depends not only on the fitting and performance of the hearing aid itself, but on a lot of different factors, many of which are of a psychosocial character. A dissertation by S. Bisgaard has recently explored these factors in Denmark and qualitatively documented their relevance (Bisgaard 2010). Thus it was natural to take up the task of trying to quantify these findings; How many Danes are satisfied with their hearing aids and for which reasons? This poster is based upon the master thesis work of Technical Audiologists Derya Ceylan and Wiebke Hudemann, University of Southern Denmark (Ceylan and Hudemann 2011).

Traditional questionnaires in the field do not focus specifically on the psychosocial aspects of hearing, so an important part of the project was to create a new questionnaire with focus on the following 5 factors:

1. Expectation of the improvement when wearing hearing aids
2. Motivation, personal or from others, for the use of hearing aids
3. The wearers social activity before and after acquiring hearing aids
4. Acclimatization to the sound from a hearing aid, and to the idea of having to use these "machines" to aid the hearing.
5. Instruction and consultancy, the things professionals can do to help getting to know the hearing aid, but also to come to terms with the situation in general.

Proceedings of ISAAR 2011: Speech perception and auditory disorders. 3rd International Symposium on Auditory and Audiological Research. August 2011, Nyborg, Denmark. Edited by T. Dau, M. L. Jepsen, J. Cristensen-Dalsgaard, and T. Poulsen. ISBN 87-990013-3-0. EAN 9788799001330. The Danavox Jubilee Foundation, 2012.