Intelligent processing to optimize the benefits of hearing aids
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Citation for published version (APA):
Boymans, M. (2003). Intelligent processing to optimize the benefits of hearing aids

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CHAPTER 7.

NOISE REDUCTION AND
DUAL-MICROPHONE DIRECTIONALITY

This chapter has been published in Audiology (Boymans et al., 2000)
7. Noise reduction and dual-microphone directionality

Summary

In this study we measured the effects of a digital hearing aid on speech perception in noise for two noise reduction concepts; noise reduction by speech-sensitive processing (SSP) and improved directionality by a dual-or so-called twin-microphone system (TMS). This was conducted in a well-controlled clinical field trial in 16 hearing-aid users, using a single-blind crossover design. The hearing aid fitting was controlled by insertion gain measurements and measurements with loudness scaling. This study combined laboratory experiments with three consecutive field trials of four weeks each. We used performance measurements (speech perception tests in background noise), paired comparisons, and self-report measurements (questionnaires). The speech perception tests were performed before and after each field trial, the paired comparisons were performed in weeks 4 and 12 and the questionnaires were administered after each field trial. For all subjects, results were obtained for three different settings: no noise reduction, SSP alone, and TMS alone. In the last week, we also performed speech perception tests in background noise with both noise reduction concepts combined. Three types of results have been reported: “objective” results from the critical S/N ratios for speech perception in different background noises for different settings and “subjective” results: paired comparisons and questionnaires. The “subjective” scores show the same trend as the “objective” scores. The effects of TMS were clearly positive, especially for the SRT-tests and for the paired comparisons. The effects of SSP were much smaller but showed significant benefits with respect to aversiveness and speech perception in noise for specific acoustical environments. There was no extra benefit for the combined effect of SSP and TMS relative to TMS alone.
7.1. Introduction

The introduction of the digital hearing aid has stimulated the application of specific features such as noise reduction and dual-microphone techniques. It is important to assess the benefits of these features for hearing-impaired people in carefully controlled field trials. The most common complaints of hearing-impaired listeners are difficulties in understanding speech in noisy environments.

Three different techniques have been developed and are available in commercial hearing instruments, but none covers the whole range of difficult listening situations. As expected, the signal processing schemes at issue need differences between the wanted signal (usually speech) and the interfering signal (usually, but not always non-speech sounds):

- If there are spectral differences between the speech signal and the noise signal, multi-channel compression may be effective for speech perception in noise by means of a relative reduction of the gain in the frequency channels with the highest intensity levels (usually caused by the noise in those channels). If, for example, these high levels are caused by low-frequency noises the noise is amplified to a lesser extent than the speech and the overall signal-to-noise ratio may be improved (although not in the individual channels) with a reduced amount of upward spread of masking. This technique has been applied already in analogue hearing aids and shows only a limited benefit in relatively specific situations (van Dijkhuizen et al. 1991; Humes et al. 1997; Moore et al. 1986; Gordon-Salant et al. 1992).

- A further refinement to benefit from spectral differences between the wanted and the unwanted signal became possible with the introduction of digital techniques for commercially available hearing aids. Where there are differences in the modulation characteristics of the speech signal and the noise signal, algorithms have been introduced to discriminate between speech and noise in each frequency channel and to adapt the gain accordingly. This feature is called modulation-based noise.
reduction. Again, the S/N ratio does not change within each channel, but the overall S/N ratio may improve in case of spectral differences between the target speech and the jammer signal. Up to the present time, only limited experimental evidence is available on the benefit of this technique. Boymans et al. (1999) found clear "subjective" preferences, but it appeared to be difficult to assess an "objectively" measured benefit in critical S/N ratio in a three-band hearing aid with noise reduction based on modulation analysis.

- Finally, if there are spatial differences between the speech signal and the noise signal, directional microphones may be effective in selective amplification of the speech (usually from the front) relative to the noise (usually from the other directions). The introduction of dual-microphone systems has renewed the interests in directionality, and various studies point out that an important benefit can be obtained in specific situations within the direct sound field of the target speaker. A number of studies point out that the application of the dual-microphone technique yields a significantly improved S/N ratio for conditions with the speaker in the direct sound field in front of the listener and the noise coming from a diffuse sound field or from other directions (Valente et al., 1995).

In commercial publications it has been suggested that new features, now available in digital hearing instruments, can compensate almost completely for the problems of listening in noise. Earlier experiences in clinical field trials, showed that a number of points need to be addressed carefully in the design of evaluation studies on advanced signal processing in hearing aids and in the interpretation of the results (Dreschler et al., 2000). The positive information in the media may strongly influence the subject's expectations and the subjective outcome measurements can easily be biased unless the test can be carried out blind. Consequently, discrepancies between "objective" and "subjective" data may be found and a careful control of the information presented to the subject is particularly important. Therefore, this study concentrates on differences
within the same hearing aid, in which the actual setting is blind for the subject, and the conditions were randomized over trial periods.

In this study we tested a full digital, four-channel, behind-the-ear hearing aid with different noise reduction strategies. We tested the combined value of the second and third noise reduction concepts. The modulation-based noise reduction concept in the trial hearing aid is called speech sensitive processing (SSP), with a possibility of activating it for each of the four frequency channels in a maximum or medium setting. The dual-microphone system in the trial hearing aid is called a Twin Microphone System (TMS). The results without noise reduction concept were compared with the results using the SSP setting and with the results using the TMS setting. For the last two settings, we used a single blind crossover design.

The fitting was evaluated by means of loudness scaling. In some cases we modified the setting of the hearing aid according to the dynamic range, the most comfortable level (MCL), and the loudness slope (Bachmann et al., 1998). For each setting used for the trial period, we measured the critical S/N ratio for sentences in noise before and after the trial period. Paired comparisons were used to find the subjectively preferred noise reduction setting for every subject in different background noises (Valente, 1994).

Finally we used the Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox et al., 1995) to evaluate the subjective judgement of the subjects according to the different hearing aid settings in the field trial. This study focuses on the following questions:

- What are the separate benefits of SSP and TMS for speech perception in noise?
- Are these effects additive if SSP and TMS are combined?
- How is user satisfaction and subjective benefit being influenced by SSP and TMS?
7.2. Method

The study combined three field trials of four weeks each with laboratory experiments before and after each field trial in order to get an indication of acclimatization (Gatehouse, 1992). The purpose of the laboratory study was to evaluate, by means of “objective” measurements, the effect of the different noise reduction settings on the critical S/N ratio. The results of the initial setting (both SSP and TMS off) were compared with the results of the two different noise reduction settings alone (SSP active / TMS off and TMS active / SSP off). Laboratory experiments included measurements of speech recognition in a speech babble (cocktail) noise and in low frequency car noise. At the beginning of the experiments, we made comparable measurements with the subjects’ own hearing aids, and after the three field trials (after three months) we measured the effect of the combination of the two noise reduction settings (SSP active / TMS active). We also applied paired comparisons to define the subjectively most preferred noise reduction setting for each subject in different background noises.

7.2.1. Subjects

We selected 16 subjects from the regular population of our audiological centre ensuring that the subjects were a representative sample of BTE-users for the fitting range of the test hearing aid. There were no restrictions, except that children (<16 years) were not included in the study and that the subjects had to be able to complete the extensive test protocol. The subjects cooperated on a voluntary basis. They had to wear the hearing aid(s) at least 4 hours a day.

The subjects had a predominantly sensorineural hearing loss (average air-bone gap < 15 dB). All subjects had at least 2 months of experience in wearing one or two BTE hearing aids. They were all carefully fitted according to the standard procedures of our
audiological centre. In 50% of the cases, the former hearing aid had advanced features such as programmability or multi-channel compression. In the test group, 12 subjects were fitted bilaterally and 4 subjects were fitted unilaterally. For unilaterally fitted subjects, the hearing aid was fitted to the better ear, and we verified that the unaided ear did not contribute significantly to speech intelligibility at the levels of testing. Table 7.1 shows some key data on the 16 subjects.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Average Hearing (.5, 1, 2, 4 kHz)</th>
<th>Fitted Ear</th>
<th>Former Hearing Aid</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>52</td>
<td>63  66</td>
<td>Right, left</td>
<td>Widex Q9</td>
</tr>
<tr>
<td>B</td>
<td>66</td>
<td>54  50</td>
<td>Right, left</td>
<td>Siemens S2+</td>
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<tr>
<td>C</td>
<td>68</td>
<td>59  51</td>
<td>Right, left</td>
<td>Siemens S1+</td>
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<td>D</td>
<td>40</td>
<td>58  68</td>
<td>Right, left</td>
<td>Danavox 143 AGC-I</td>
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<td>E</td>
<td>66</td>
<td>42.5 -</td>
<td>Right</td>
<td>Widex ES8</td>
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<td>F</td>
<td>51</td>
<td>60  68</td>
<td>Right, left</td>
<td>Widex L12E</td>
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<td>G</td>
<td>75</td>
<td>49  55</td>
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<td>Danavox 143 AGC-I</td>
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<td>66</td>
<td>56  58</td>
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<td>P</td>
<td>68</td>
<td>48  44</td>
<td>Right, left</td>
<td>Oticon Personic 410</td>
</tr>
</tbody>
</table>

Table 7.1. Summary of individual data on the participating subjects.

7.2.2. Hearing aids

The test hearing aid was a digital BTE hearing aid (Siemens Prisma). This hearing aid is equipped with two user-controlled programs, which can be switched without a remote
control. There is no external volume control at the disposal of the user (for more details, see Holube (1998).

As described, one of the features under test is the modulation-based noise reduction (called SSP). Speech can be described with respect to its temporal structure or its frequency distribution in the spectrum. Typically, the spectrum of speech shows frequency components between 100 Hz and 8 kHz. The envelope of the signal, which is only changing slowly and has therefore much lower frequencies than the spectrum, is often not taken into account. The envelope of the speech is determined by phonemes, syllables, words, and sentences. Voices can normally articulate about 12 phonemes, 5 syllables, and 2.5 words per second. To formulate a sentence, several seconds are necessary. Therefore, the envelope of speech shows a characteristic temporal behaviour that is, in general, independent of the speaker or the spoken language. The envelope is a characteristic feature of signals that now can be used in hearing instruments. The modulation spectrum is different for speech and for most types of background noise. The maximum in the modulation spectrum of speech is in the area of 2 to 8 Hz. The modulation spectrum of noise usually shows fewer and faster modulations and therefore has its maximum at higher frequencies. This difference in the modulation spectra between speech and noise can be used to detect speech and to reduce the noisiness of the signals. A reduced noisiness can result in a more comfortable sound, a reduced hearing effort, and an increased speech intelligibility. For this purpose, the envelope of the signals is analysed in different frequency channels. If the characteristic modulation frequencies of speech are detected, the speech is amplified according to the requirements of the hearing loss. If the characteristic modulation frequencies of speech do not exist in the signal, the gain in that frequency channel is reduced. The gain reduction is higher for higher modulation frequencies and lower modulation depth. The largest gain reduction is achieved for stationary signals like sinusoids or white noises. The value of the largest gain reduction can be selected independently in each frequency channel and can be set to medium (5 dB) and maximum (10 dB). In addition, it is of
course possible to deactivate the processing algorithm in each frequency channel.

The second feature is the Twin Microphone System (TMS). By using a combination of two microphones, directionality can be improved considerably. The amount of improvement can be expressed as a front-random index, which is usually higher for the higher frequencies. Merks (2000) measured front-random indices for the Siemens Prisma hearing aid in an artificial diffuse sound field. For the AI-weighted front-random index, he found values of $-1.4$ dB for the test hearing aid with omni-directional microphone and $+3.3$ dB for the test hearing aid with TMS. Thus the acoustical gain in front-random index for the TMS-system is $4.7$ dB.

All subjects started in an individually selected basic setting (see chapter on fitting) without noise reduction or directionality for both programs (programs P1 and P2 were exactly the same), in order to adjust to the hearing aid. After four weeks, one of the two noise reduction schemes (SSP or TMS) was activated in program P2. Again, after four weeks, we changed the noise reduction concept in program P2, according to a randomized scheme.

The subjects had no information about the differences between the noise reduction concepts in program P2. They were told that they had a second program in the hearing aid and were asked to use it in different situations. They knew that after each field trial they had to fill in a questionnaire about the different programs.

7.2.3. *Fitting procedure of the digital hearing aid*

All hearing aids were fitted in a quiet surrounding. The frequency response and compression parameters were based on the hearing thresholds and uncomfortable levels according to desired sensation level (DSL) (input/output) (Cornelisse et al. 1995) using the individual real ear unaided response. We checked the target setting objectively by
means of insertion gain measurements with speech-shaped noise (according to long-
term average speech spectrum, LTASS, Byrne et al. 1994) at input levels of 50, 65, and
80 dB(A). If feedback problems occurred, we modified the ear moulds. When the ear
mould was correct and there was still a feedback problem we did some fine-tuning
according to the manufacturer-provided recommendations (the so-called Fitting
Assistant in the programming software).

In addition, we applied a subjective check of the target setting by means of loudness
scaling. Aided loudness scaling was performed for each ear using the Würzburger
Hörfeld Skalierung (WHS), which is based on a 50-point scale (Kiesling 1995). We
used narrow band noises with a duration of 5 seconds, the ranges of output levels were
30 to 90 dB(SPL). During this measurement, the noise reduction concepts were
inactivated. We applied curve fitting to reduce measurement error. The fitting resulted
in two parameters: the level at which the loudness level of 50% of the scale was reached
(called MCL) and the slope of the loudness growth function. The former is related to the
degree of hearing loss, the latter to the amount of recruitment. For the verification of the
fitting, the correspondence between the aided loudness contours and the normal
loudness contours was considered.

The decision for fine-tuning was always based on a combination of different factors: the
sound impression of the subject, the insertion-gain measurements, and the results of the
aided loudness scaling. Generally, the complaints were the same: most subjects found
the initial settings of the hearing aid too loud. When the loudness curves were too steep
we gave more compression for that particular frequency band, and when the loudness
curve was shifted we adapted the gain for that particular frequency band. We were
reluctant to perform further fine-tuning when the subject still had some complaints, but
when the results of the WHS were in agreement with the loudness curves of a normal-
hearing person. In that case we tried to persuade him/her to start trying the hearing aid
for one week. When the subject could not get used to the hearing aid, we performed
some fine-tuning after one week, according to the suggestions of the Fitting Assistant in the fitting software (but as little as possible). We always repeated the insertion gain measurements and the WHS-measurements for the final setting.

Fortunately, there were only slight differences between the initial and final fittings for the majority of the subjects. These differences may be assumed not to influence the differences between the noise reduction schemes under test, because the same ear moulds and the same basic settings were used throughout the remainder of the experiments.

### 7.2.4. Performance with speech in noise

For each setting used for the trial periods, we measured the speech-reception thresholds (SRTs) for sentences in background noise, according the method of Plomp and Mimpen (1979), before and after the trial period. This test uses an adaptive up-down procedure and has been proven to be relatively fast and accurate (test-retest standard deviation between 0.9 to 1.5 dB). We used two different speakers (male and female, at $0^\circ$ azimuth), and two different background noises (cocktail noise and car noise\(^1\)) coming from three uncorrelated noise sources (at $90^\circ$, $180^\circ$, and $270^\circ$ azimuth). The speech material from the male voice was presented in cocktail noise and the speech material from the female voice was presented in car noise (the spectral differences are shown in Figure 7.1a and 7.1b, respectively).

\(^1\) Tracks 50 and 54 from the cd "Fitting and testing of hearing programs", produced by Colosseum Musikstudios, 1992.
The spectra show clearly that the spectral differences between the male speaker and the cocktail noise are only marginal, whereas there are marked spectral differences between the car noise (with more low-frequency emphasis) and the female speaker (with more high-frequency emphasis).
We used an adaptive procedure to find the 50\% point by changing the S/N ratio. The noise level was fixed at 65 dB(A) at the listener’s position. The speech level was calibrated by a continuous noise with an identical spectrum of the speaker, expressed as equivalent long-term rms level in dB(A) (without silent gaps). The results will be reported in terms of the S/N ratio at threshold (the so-called critical S/N ratio). Testing was performed with 20 lists of sentences. The order of the lists was randomized. In previous studies the psycho-acoustical measurements have been severely hampered by the long adaptation times of noise-reduction algorithms (Boymans et al. 1999). In this study, we applied speech testing in noise and the noise was constantly present during testing. The SRT-test was performed with the subject’s own hearing aid, before and after the field trials without the noise reduction concept, with TMS (pre- and post-trial) and with SSP (pre- and post-trial); in the end, we also performed the SRT-test with both noise reduction concepts (TMS active and SSP active).

7.2.5. Paired comparisons

The subjective preferences for the hearing aid settings under test were investigated by means of the technique of paired comparisons (Eisenberg et al., 1997; Kuk, 1994) in week 4 (after the first field trial: test) and week 12 (after the last field trial: retest). Four different hearing aid settings were tested. (SSP off / TMS off, SSP active / TMS off, SSP off / TMS active, and SSP active / TMS active). The subjects were asked to listen to standard speech fragments and state which program they preferred when they had to understand speech in “this situation” through the whole day. The choice was always one of two programs. Six combinations were possible. As with the SRT-test, two background noises were used (cocktail noise and car noise). The noises came also from three sides (90°, 180°, and 270°) the speech came from 0° azimuth. Thus, in total, the subjects had to make twelve choices (test). During the changing of programs, the noise remained on. For each noise at 65 dB(A), the same two sentences were used at 70
Noise reduction and dual-microphone directionality

dB(A). When the subjects could not choose, they were allowed to hear the speech samples again.

7.2.6. Self report

In the first trial period, each subject became accustomed to the sound of the new hearing aid. After the first week, the subject was asked to fill in a questionnaire about general aspects (sound quality, speech intelligibility, and own voice) of their new hearing aids using visual analogue scales (not reported in this paper).

To compare the different settings of the test hearing aid we used a Dutch version of the APHAB questionnaire (Cox 1995). APHAB is a subjective assessment scale that measures the benefit from amplification. It consists a set of 24 items (a sub-set of the original PHAB questions) and yields scores in four sub-scales:

1. EC: ease of communication, the strain of communication under relatively favourable conditions.
2. RV: reverberation, communication in reverberant rooms.
3. BN: background noise, communication in settings with high noise levels.
4. AV: aversiveness of sounds, the unpleasantness of environmental sounds.

Each item is a statement. The subject is asked to indicate if that statement is true using a 7-point scale. We asked the subject to fill in the APHAB in different situations: in week 0, without a hearing aid and with their own hearing aid; in week 4 (after the trial period with the new hearing aid without a noise reduction concept); in week 8 (after the trial period with a noise reduction concept in program P2); and in week 12 (after the trial period with the other noise reduction concept in program P2). The aided scores (with the own hearing aid) obtained at week 0, were used as a reference score in week 4. After that, the scores of the new hearing aid (O+O) were used as a reference score (in weeks 8 and 12).
7.3. Results

We will present three types of results: SRT measurements with the subject’s own hearing aid and with different settings of the digital hearing aid, paired comparisons with different hearing aid settings, and subjective data obtained by the APHAB.

7.3.1. Performance on speech perception in noise

Figure 7.2 presents the results of the SRT test for the total group (n=16). The left group of bars represents the critical S/N ratio of a male voice in speech-babble (cocktail) noise; the right group represents the critical S/N ratio of a female voice in car noise.

The first bars of both groups represent the critical S/N ratio of the own hearing aid. For the test hearing aids, two measurements are available (before and after each trial period). There were no significant learning effects. Therefore, pre- and post-trial results have been averaged. The second, third, and fourth bars represent these averaged critical S/N ratios for the different hearing aid settings: SSP off / TMS off (O+O), SSP off / TMS active (O+D), and SSP active / TMS off (N+O), respectively. The subjects did not have a trial period with both noise reduction concepts active (SSP active and TMS active (N+D)), so we made only one measurement (see the fifth bar in Figure 7.2). The statistical significance of the differences between the hearing aids was tested by means of Wilcoxon-tests (matched pairs signed ranks).
It is clear that, on average, there were no differences between the scores of the own hearing aid and the new hearing aid without noise reduction strategies. The settings with TMS active showed a clear improvement in critical S/N ratio with respect to the setting without noise reduction (p<0.01 for cocktail noise, p<0.05 for car noise). There also appeared to be some improvement for the setting with SSP active, but this was only modest (n.s.). The combination of both noise reduction concepts (N+D) does not give an added value relative to the setting with the TMS active only (O+D). The trends of the results in cocktail noise and in car noise were similar. As expected, the overall thresholds in car noise are better (lower S/N ratios) than in speech noise.
7.3.2. Subjective data on paired comparison

Figure 7.3 presents the results of the paired comparisons for different hearing aid settings in different noises. The first set of bars shows the percentages of preferences without any noise reduction setting. The second set shows the percentage of preferences with the TMS active, the third set with SSP active, and the last set with both noise reduction algorithms active. The preference for the TMS setting is almost 60% higher than for the setting without noise reduction (p<0.001 for a sign test). The subjects prefer the SSP setting less than the TMS setting, but the preference is 10-20% higher than the setting without noise reduction (p<0.001 for a sign test). There is not much difference when the SSP is added to the TMS. In general, there is only little difference between the preference in speech noise and in car noise.

![Graph showing preference percentages](image)

**Fig. 7.3.** Percentage preferences for the different settings of the test hearing aid, measured by paired comparisons in cocktail noise and in car noise: O+O: without SSP, O+D: with TMS, N+O: with SSP, N+D: with SSP and TMS.
7.3.3. **Comparison of the “objective” (SRT) and “subjective” results (PC)**

Figure 7.4 presents the “subjective” results of the paired comparisons versus the “objective” results of the SRT-tests in different noises. Three effects can be distinguished from this figure:

- The points for the car noise are shifted to more negative S/N ratios because of the “objective” thresholds in car noise are better than in cocktail noise.
- For each of the noises the “subjective” and “objective” results are well in agreement. When better SRT-thresholds are found (lower critical S/N ratios for a hearing aid setting), the subjective scores of the paired comparisons become also better (a higher preference for that particular setting). The scores with SSP alone (N+O) are slightly better than without noise reduction (O+O). A much better result is obtained when the TMS-setting is active (O+D), but the combination SSP and TMS (N+D) does not give added value relative to TMS alone.
- The pattern is comparable for both noise types, which suggests that the effects described are insensitive for the type of background noise and the S/N ratio of the signal presentations.

![Subjective vs. objective results](image)

**Fig. 7.4. Correspondence between "subjective" and "objective" results for the four hearing aid settings in cocktail noise and in car noise.**
7.3.4. Subjective data from the field trial questionnaires

Figure 7.5 shows the results of the APHAB questionnaires, which were summarised in four sub-scales: ease of communication (EC), reverberation (RV), background noise (BN) and aversiveness of sounds (AV). All sub-scales are expressed as percentages of problems. Consequently, lower values indicate better results.

The response pattern shows that the use of a hearing aid (relative to unaided) reduces the percentage of problems drastically, partly at the cost of a higher aversiveness. Despite the fact that some subjects indicated that the test hearing aid was relatively loud in the beginning, the aversiveness for the test hearing was slightly lower than for the own hearing aid. This can be an indication that, in those subjects, an adequate limiting of high output levels compensates for the higher gain values. However, these data are subjective and can also be biased by a preference for the new digital hearing aid per se.

Fig. 7.5. APHAB scores for the different hearing aids and/or hearing aid settings. Own: own hearing aid, O+O: test aid without noise reduction, O+D: test aid with TMS, N+O: test aid with SSP. EC: ease of communication, RV: reverberation, BN: background noise, AV: aversiveness of sounds
In this respect, the comparisons between the different settings of the test hearing aid are more informative.

For this study, the effects of SSP and TMS are of particular interest. When we consider the differences between the settings in the test hearing aid, few effects were statistically significant. Only the effect of TMS on aversiveness (the difference between O+D and O+O) is significant at p<0.05 (Wilcoxon matched-pairs signed-ranks test). The absence of other significant effects may be due to the fact that the APHAB sub-scales are composed of six answers to questions for different conditions, while possible benefits may be present for only some of them. Therefore, we analysed the answers to the individual questions for SSP (N+O versus O+O) and for TMS (O+D versus O+O) by means of a sign test. These data were obtained by direct comparison during the second and third field trials.

Positive effects of SSP were statistically significant for speech perception in car noise (p<0.05) and for the aversiveness for sudden loud sounds like alarm bells (p<0.01) and traffic noises (p<0.01). Positive effects of TMS are found for all six questions on aversiveness (4 effects with p<0.01) and for three questions on speech perception in noise: in car noise (p<0.01), in a conversation with one person at dinner with several people (p<0.01), and for a conversation in a crowd (p<0.01).

7.4. Discussion

In spite of the careful fitting procedures applied, the results obtained with the test hearing aid without special processing (O+O) are no better than the results of the subjects’ own hearing aid. This suggests that digital technology per se does not help the main problem of hearing-impaired listeners, which is speech perception in noise. However, digital technology facilitates the use of modulation-based noise reduction and the application of dual-microphone techniques. This may bring additional benefits:
Noise reduction is a system that can distinguish speech from noise on the principle that there is a difference of the modulation spectrum between speech and noise. So, if the modulation frequencies of speech do not exist in the signal, the gain in that frequency channel is reduced. For that reason increased speech intelligibility in background noise (especially when the noise deviates from speech, for example, constant low frequency noise) and a more comfortable sound can be expected.

The dual-microphone technique improves directionality. Thus, the spatial separation of speech and noise favours the sounds from the front. Here also, increased speech intelligibility in background noise and a more comfortable sound can be expected, although the effectiveness is not dependent on the spectral difference between speech and noise.

It is important to test the benefit of these developments in the field. However, there are many aspects to be taken into account. It is difficult to do a blind study because different hearing aids are often needed. However, in our experimental design, bias was minimised by comparing different settings in the same hearing aid. However, each comparison with the subject’s own hearing aid may be biased because he/she knew which was their own and which was the new hearing aid. Another aspect we have to take into account is the adaptation effect. This is avoided by a common adaptation period for all subjects. In our set-up, all subjects had the same reference. After the adaptation period, two conditions (SSP and TMS) were tested successively, with the order randomized.

Laboratory tests do not always resemble the real-life situation. In our study we used a nice combination of field trials with questionnaires and “objective” SRT-tests in two different background noises coming from three sides. Direct comparisons could be made in the paired comparison test also in two different background noises coming from three sides.
The fitting of the test hearing aid was very comprehensive (and thus time consuming). Individual differences of the ear canal and the ear moulds were taken into account. For the target fitting, the real ear unaided response was used and the fitting was checked by insertion gain measurements. A number of subjects judged the gain prescribed by the DSL(i/o) as relatively loud. This is in agreement with other studies (Stelmachowicz et al. 1998). Fine-tuning was done when the loudness scaling deviated too much from the reference curves.

The positive effects of SSP are relatively small. In the SRT results, the improvements due to SSP (N+O re. O+O) are not significant and in car noise they are hardly better than in cocktail noise. Our hypothesis that SSP would be more effective for a constant noise with a spectrum that deviates from speech (like car noise) than for a fluctuating noise with a speech-like spectrum (like cocktail-party noise) cannot be confirmed in the performance data. However, SSP adds to the subjective benefit as shown in the preference data of the paired comparisons. Although the effects of SSP were not significant for any of the APHAB sub-scales, some of the specific questions showed significantly better scores (e.g. regarding speech perception in car noise and some questions on aversiveness).

The positive effects of the TMS are obviously present in the results of the SRT-test, the paired comparison, and the questionnaires. For the SRT-test there is a clear difference between the results with the TMS active and the initial setting (no SSP no TMS). The first results are in agreement with the results of Wouters et al. (1999) and Ricketts et al. (1999). The degree of improvement in the SRT data of this study (4.5 dB, both for the cocktail noise and for the car noise) is close to the gain that can be expected on the basis of acoustical measurements (4.7 dB according to Merks, 2000). However, it is slightly smaller than the 5.7 dB gain that was observed in a recent study by Pumford (2000). Ricketts and Dhar 1999a described results of the combination of SSP and TMS in a living room environment (the noise came from five different directions). Although not
significant, they found a better score for a nonsense syllable test with both SSP and TMS active compared with TMS alone. In our results, the combination of SSP and TMS was not significantly better than TMS alone, for either the SRT results or for the paired comparisons. So, in this experiment, there is no added value of both TMS and SSP (N+D) relative to TMS (O+D). It is possible that the lower gain for the background noise due to TMS made further noise reduction by SSP less necessary or at least more difficult to perceive.

For the sub-scores of the APHAB questionnaire, there is only a significant difference for the sub-scale aversiveness (O+O vs. O+D). The reason could be that a lot of answers were already positive for the setting O+O so there was not much space for further improvement. Also, the analysis of the effects of SSP and TMS on the separate questions revealed that significant effects might easily disappear when conditions are combined in which possible positive effects are only found for a sub-set of the conditions. The positive effect of TMS on aversiveness is unexpected. One reason may be that the overall loudness impression of the test hearing aid in the directional mode is softer (the subjects have no volume control). However, the gain reduction in the low frequencies for the directional mode is likely to be the most important reason.

The paired comparison is a subjective test, but in contrast of the APHAB it is always in the same acoustical situation. It is important always to give the same instruction. Many subjects will choose O+O when the instruction is “which program is the best”. In principle, they want to hear everything. But when is added: “when you have to sit in this situation for a long time”, they will choose a more quiet setting. The paired comparisons are in agreement with the SRT-test. The lowest scores are obtained without noise reduction, better scores were found with SSP active and the best scores with TMS active. Here also the two noise reduction settings are no better than TMS alone.

However, the results of SSP alone tend to be more favourable than in the SRT-tests. The SRT-test is a threshold measurement (S/N ratio is variable) and the paired comparisons
were measured at fixed S/N ratio (S/N = 5 dB). For most subjects this was well above their speech reception thresholds in noise, for car noise more than for cocktail noise. The critical S/N ratios of the SRT results without noise reduction are between −4 and −7 dB. At such a poor S/N ratio it can be that the noise reduction does not work well, which could be the reason why the SSP does not improve scores significantly. Therefore, positive effects are only found in the paired comparisons where, usually, a better S/N ratio (+5 dB) has been used.

The "subjective" scores from the questionnaires are in reasonable agreement with the "objective" scores. For the subjective questionnaires, more attention is paid to different situations. The scores of the questionnaires show no difference in ease of communication (EC) for the different hearing aid settings in relatively favourable conditions. We did not use this relatively favourable condition (speech intelligibility in quiet) in the "objective" tests. In spite of the fact that some subjects indicated that the test hearing aid was relatively loud in the beginning, the aversiveness scores for the test hearing aids were better than for the own hearing aids. This can be an acclimatization effect because in the end of the four weeks, most subjects did not find the hearing aids too loud.

We also analysed the effects in different subgroups. The differences were not significant, but some of the trends will be described below. The eight subjects with the most sloping audiogram scored better in cocktail noise and worse in car noise relatively to the average of the whole group. This can be due to upward spread of masking and the reduced capacity to use high-frequency information for the group with sloping losses. The eight subjects with the worst SRT-scores in the O+O setting do score below the average of the whole group for all other SRT-tests. The trends of SSP and TMS are similar in both subgroups. The type of hearing aid used before (conventional or advanced) did not influence the results either.
In the end all subjects wanted to purchase the test hearing aid. Most of the subjects were allowed to obtain a new hearing aid. A few subjects determined to replace their own hearing aid. Nine of 16 subjects chose the combination P1: O+O and P2: O+D; 3 subjects chose P1: O+O, P2: N+O; 3 subjects chose P1: N+O, P2: O+D and one subject chose P1: O+D P2: N+D.

7.5. Conclusions

In our group of hearing-aid users, the following conclusions can be drawn:

- Positive effects of SSP are only modest. No significant differences for SRT were found but APHAB-scores were significantly better for some specific questions.
- Positive effects of TMS (O+D vs. O+O) are significant both for SRT-thresholds and paired comparisons. APHAB results show significant effects for aversiveness and for some conditions in background noise.
- There was no extra benefit for the combined effect of SSP and TMS relative to TMS alone (N+D vs. O+D).