Perceptual evaluation of noise reduction in hearing aids
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Acoustical and perceptual comparison of noise reduction and compression in hearing aids

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To be submitted for publication
5.1 Introduction

Noise reduction and dynamic-range compression are common features in modern hearing aids. The role of noise reduction is to reduce hearing aid gain for background noises and to preserve the gain for incoming speech signals (Bentler and Chiou 2006). The role of compression is to adjust the hearing aid gain based on the input level to fit all incoming signals into the restricted dynamic range of the hearing aid user (Dillon 2001). Compression results in more amplification of low input levels and less amplification of high input levels. Studies investigating the perceptual effects of noise reduction and compression have provided inconsistent results. In general, both the features do not appear to or only slightly influence speech intelligibility in noise; however, both noise reduction and compression can provide benefit in terms of listening comfort and effort. The optimal settings for intelligibility may however differ from the optimal settings for sound quality, both for noise reduction and compression (Dillon 2001; Anderson et al. 2009; Chapters 4 and 6).

Compared with compression, only limited literature is available on noise reduction in hearing aids. This may be because noise reduction in hearing aids is commonly presented as a “black box” i.e., there is no information on the details of signal processing. While compression ratios of a hearing aid can be manually adjusted as a function of frequency, noise reduction can only be influenced by switching an unknown algorithm on or off, with in some hearing aids a few options for processing strength (e.g., “mild”, “moderate”, or “strong”). Because of the broad application of noise reduction in hearing aids, these relatively large uncertainties about its implementation are unexpected and undesired.

Although noise reduction and compression are generally applied together, literature on possible interactions between them is scarce (Chung et al. 2007; Anderson et al. 2009). Because noise reduction should reduce the noise level and compression should increase low-level sounds, it is possible that both the features counteract each other, based on their configuration and on the level of background noise. Chung (2007) found that in some hearing aids, the combination of noise reduction and compression caused lesser reduction of noise level than noise reduction alone (i.e., in a linear setting). However, in other hearing aids, compression did not or even positively influence the effect of noise reduction on noise level. Therefore, implementation of noise reduction and compression differ largely between hearing aids, making it difficult to investigate their effects systematically and to draw conclusions that can be generalized across hearing aids.
In the current study, we evaluated the combination of noise reduction and compression in a small set of hearing aids in three subsequent steps. In Experiment 1, we performed acoustical analyses to measure how compression and noise reduction influenced the gain in four different hearing aids. In Experiment 2, we determined whether changes in gain caused by noise reduction and compression were audible in hearing-impaired listeners using three of the above hearing aids. We looked at differences between conditions within hearing aids as well as at differences in identical conditions between hearing aids. Comparisons between hearing aids were possible because we corrected the differences in frequency response between hearing aids by using inverse filters (see Chapter 2). In Experiment 3, we determined whether combined processing of noise reduction and compression influenced intelligibility and preference compared with (a) no processing (i.e., linear gain only) and (b) combined processing in other hearing aids.

5.2 Experiment 1: Acoustical evaluation

Because most manufacturers do not provide details on the implementation of compression and noise reduction, we can use acoustical analyses to gain an insight into how these features react to speech in noise signals. Therefore, we analyzed recordings of four different hearing aids to answer the following question:

Q1: How do noise reduction and compression, separately as well as in combination and in different hearing aids, react to speech in babble noise at an input SNR of +4 dB in terms of (a) dynamic gain patterns and (b) change in the overall speech and noise levels?

5.2.1 Methods

Hearing aid recordings

The study included four brands of frequently used behind-the-ear hearing aids (Phonak Exélia M, ReSound Azure AZ80-DVI, Starkey Destiny 1200, and Widex Mind 440) that were randomly assigned a number (from HA1 to HA4). This designation was same as that employed in Chapters 3 and 4, but differed from that employed in Chapter 2.

For linear conditions, we applied the same methods of hearing aid fitting and recording as those described in Chapter 2. We took the hearing aids, hearing aid settings, and equalization filters from the test set in Chapter 2 so that we were sure that the verification of the method was also applicable to the new recordings. All the signal-processing features in the hearing aids (directionality, feedback control, noise reduction, compression, frequency transposition, etc.) were turned off, and the frequency-gain patterns of
the hearing aids were carefully adjusted to obtain a linear gain that was the same for all hearing aids.

For compression conditions, we fitted the same hearing aids so that their insertion gain, as determined on a B&K Head and Torso Simulator (HATS Type 4128C), was in accordance with the NAL-NL1 prescription for the audiogram coded as N3 from the set of standard audiograms proposed by Bisgaard et al. (2010).

We recorded all sound signals in four different conditions per hearing aid: linear with noise reduction turned off (“Unprocessed” condition), linear with noise reduction turned on (NR), compressive with noise reduction turned off (C), and compressive with noise reduction turned on (CNR).

We designed inverse filters for each hearing aid to remove differences in frequency response that remained among the hearing aids (see Chapter 2). Two filters were designed for each hearing aid: one to correct the differences in gain in the linear setting and another to correct the differences in gain in the compressive setting. After filtering, the spectra of recordings of stationary noise with an input level of 65 dB SPL were equal for conditions with noise reduction turned off, both for the linear and compressive hearing aids. For linear hearing aids, the inverse filter also corrected the differences in gain between hearing aids at other input levels. However, for compressive hearing aids, only the gain for an input level of 65 dB SPL was equalized. Because of differences in compression ratios as a function of frequency, the gain of compressive aids for other input levels may have slightly differed between hearing aids. These remaining differences in gain between compressive hearing aids are shown in Figure 5.1. This figure shows an effective gain (i.e., the difference between the original input signal and the filtered recording) for stationary noise with input levels of 55 dB SPL (upper curves), 65 dB SPL (middle curves) and 80 dB SPL (lower curves) for hearing aids HA1-HA4. The target that is plotted is the NAL-NL1 prescription for the N3 audiogram. While the gain curves for 65 dB SPL input level agree well between hearing aids caused by the inverse filter, the gain for other input levels differs due to limitations in hearing aid fine-tuning to compensate for detailed differences in amplitude compression. For instance, hearing aid HA3 applied compression for frequencies below 500 Hz although linear gain was prescribed for those frequencies. HA3 did not allow a change in low-frequency compression without affecting the compression at higher frequencies.

In addition to the inverse filter, we bandpass filtered the recordings to limit the response to frequencies ranging from 100 Hz to 5800 Hz.
Figure 5.1: Hearing aid gain after filtering for each hearing aid (from HA1 to HA4) for input levels of 55 dB SPL (upper curves), 65 dB SPL (middle curves) and 80 dB SPL (lower curves). The thick lines show the NAL-NL1 prescription for a moderate sensorineural hearing loss according to the N3 audiogram as defined by Bisgaard et al. (2010).

Sound signals
We made hearing aid recordings of female speech from the Dutch VU98 speech material (Versfeld et al. 2000) in a multitalker babble noise. The signals were presented to each hearing aid with an average noise level of 65 dB (A) and an SNR of +4 dB. The babble noise was played continuously while the speech was paused for approximately 1 s between sentences. One list (approximately 36 s) preceded the list that was used for analysis in each condition to allow the noise reduction algorithm in each hearing aid to adapt to the input signals.

To obtain additional acoustical information on the effect of signal processing, we applied the method described by Hagerman and Olofsson (2004). This method allows the calculation of speech and noise levels separately after hearing aid processing by making an additional recording with the noise inverted before it was combined with the speech and presented to the hearing aid. The speech and noise levels can then be separated by taking the sum or the difference of both the recordings.

5.2.2 Results
Figure 5.2 shows the effects of different hearing aid settings on the signal for a recorded sentence. The hearing aid output is plotted as a time signal in gray with the background in dark gray indicating the unprocessed condition (Unpr) and the foreground in light gray indicating the processing condition NR, C, or CNR. The spectrogram-like color plots show the difference between the processing condition (NR, C, or CNR) and the unprocessed condition (Unpr) as a function of time and frequency. The more negative the gain value, the stronger the gain reduction induced by the processing. Thus,
Figure 5.2: Acoustical effects of noise reduction and compression in the four hearing aids tested for a sentence in babble noise with an input SNR of +4 dB. The left column shows the effect of compression (C-Unpr), the middle column the effect of noise reduction (NR-Unpr) and the right column the effect of combined processing of noise reduction and compression (CNR-Unpr). For each processing condition, the time signal of the hearing aid output is shown for the unprocessed condition (dark gray background signal) and for the condition with processing on (C, NR, and CNR respectively for the three columns, the light gray foreground signal). The spectrogram-like color plots show the difference between processed and unprocessed conditions as a function of time and frequency.

Red areas correspond to more gain reduction due to processing, whereas blue areas represent no processing or even an increase in gain (dark blue).

Figure 5.3 shows the results obtained with the inversion method of Hagerman and Olofsson (2004). For each processing condition, we extracted the output speech and output noise by respectively adding and subtracting the two recordings with inverse noise from each other. We compared the resulting speech and noise levels after processing with those obtained in the same way for the unprocessed (Unpr) condition. Figure 5.3 shows level reductions in speech and noise signals separately for each processing condition, averaged over 13 sentences.
Figure 5.3: Average reduction in speech and noise levels due to the processing of the speech in babble noise at an input SNR of +4 dB. The left panel shows the effect of compression (C), the middle panel shows the effect of noise reduction in a linear setting (NR), and the right panel shows the effect of the combination of noise reduction and compression (CNR), all relative to the unprocessed condition (Unpr).

5.2.3 Discussion

The processing of noise reduction (middle column in Figure 5.2; NR-Unpr) differed between the hearing aids in gain depth and dynamics, which was previously shown in Chapter 3 (Figure 3.1). NR4 did not change the gain at this input SNR. All other noise reduction algorithms reduced the noise level more than the speech level (Figure 5.3). Although this implies that noise reduction improves the SNR, it does not necessarily mean that noise reduction also improves intelligibility (Chung 2007). For instance, the sections of the noise that were removed were not necessarily the sections that masked the speech. In addition, the audibility or quality of speech may have been affected, as indicated by the reduced overall speech level. However, Wu and Stangl (2013) found that the changes in SNR as calculated with the method of Hagerman and Olofsson (2004) were related to the changes in acceptable noise level (ANL) of subjects. Thus, although changes in the estimated output SNR cannot directly be translated to an improvement in intelligibility, they may point at other perceived benefits of processing (see Experiment 3).

The changes in gain pattern caused by compression (C-Unpr; left column in Figure 5.2) were similar between hearing aids, except C4, which appeared to have much longer release times than other compression conditions (i.e., the compression reacted relatively slowly to a decrease in input level). Figure 5.3 shows that compression in hearing aids HA1-HA3 reduced speech level more than noise level, which is common for positive input SNR because the speech level was higher than the noise level; thus, speech was less amplified than noise (Hagerman and Olofsson 2004; Rhebergen et al. 2009; Wu and Stangl 2013).
The combined processing of noise reduction and compression (CNR) resulted in the strongest reduction in signal levels, except in hearing aid HA4. Because noise reduction reduced gain in noise and compression during speech, their combined effect on speech and noise showed a relatively constant reduction in gain (Figure 5.2, particularly for CNR1 and CNR2). Although it is imaginable that noise reduction and compression could cancel each other’s effect on the gain (e.g., when compression increased the noise level decreased by noise reduction (Chung 2007; Anderson et al. 2009)) it was not the case in the hearing aids tested.

Wu and Stangl (2013) also used the Hagerman and Olofsson (2004) method to evaluate signal processing in hearing aids. They used a different hearing aid; however, within that hearing aid, they evaluated the same conditions as we did (unprocessed, NR, C, and CNR). With the hearing aid and speech in speech-shaped stationary noise at an SNR of +5 dB, they found the same ranking of conditions in their output SNR (note that the change in output SNR in our hearing aids can be derived from the difference between speech and noise levels in Figure 5.3). Activating noise reduction in the linear setting improved the SNR, whereas compression reduced SNR compared with linear gain. When noise reduction was activated in the compressive setting, the negative effect of compression on SNR was offset by noise reduction; however, the output SNR did not reach the same level as that in the linear noise-reduction setting (Wu and Stangl 2013).

5.3 Experiment 2: Detectability of differences

Acoustical measurements showed different strategies for noise reduction and compression between hearing aids. However, it is not known whether these differences are perceptually relevant. As a first step to investigate this, we determined whether the differences could be detected by hearing-impaired listeners for different combinations of conditions within as well as between hearing aids. To limit the number of conditions, we left out hearing aid HA4 because the spectrogram did not show any changes in gain due to noise reduction in this hearing aid at an SNR of +4 dB.

We designed a listening experiment to determine the percentage of correct detection of differences between conditions to answer the following questions:

Q2. Can hearing-impaired listeners distinguish between combined processing of noise reduction and compression and (a) no processing (CNR compared with unprocessed within each hearing aid) and (b) combined processing of other hearing aids (CNR compared between hearing aids)?
Q3. Can hearing-impaired listeners detect the effect of noise reduction equally well within a linearly fitted hearing aid (NR compared with unprocessed within each hearing aid) as that within a hearing aid fitted with compression (CNR compared with C within each hearing aid)?

Q4. Are there any audible differences between hearing aids that are fitted according to the same compressive fitting rule (NAL-NL1) after correction for differences in their frequency response at an input level of 65 dB SPL (C compared between hearing aids)?

Questions Q2 and Q3 were meant to provide insight on the effects of noise-reduction processing in compressive hearing aids. Question Q4 was meant to investigate whether careful hearing aid fitting and inverse filtering could remove audible differences between compressions in the tested hearing aids.

5.3.1 Methods

Hearing aid recordings
We used the recordings of speech in babble noise with an input SNR of +4 dB from hearing aids HA1-HA3, which were also used in Experiment 1.

Subjects
Twenty listeners with a moderate sensorineural hearing loss who participated in the study in Chapter 4 were invited for a second visit. Of these, 16 participated in this study. The four remaining subjects did not participate for personal reasons. We used the original audiograms of the subjects because their hearing loss had not deteriorated by ≥10 dB in the intervening period (approximately 10 months), determined during the second visit by measuring their air-conduction hearing thresholds of 0.5, 1, 2, and 4 kHz for the ear included. To use the same compression ratios for all participants, only subjects with an audiogram resembling that of the standard audiogram N3 (Bisgaard et al. 2010) were included. Figure 5.4 shows the hearing thresholds for the ears included in the experiment averaged over all the subjects, the corresponding standard deviations, and the standard audiogram N3.

Amplification
The NAL-NL1 prescription rule yields slight differences in the prescribed gain and compression characteristics for individual subjects. The differences between prescribed compression ratios in individual subjects appeared to be small because subjects with audiograms very close resembling the N3 audiogram were selected (Bisgaard et al. 2010; also see the group-average audiogram in Figure 5.4). Therefore, we could use the recordings made for Experiment 1.
The differences in prescribed gain for an input level of 65 dB SPL differed more between individual subjects than relative differences in gain between input levels caused by different compression ratios (i.e., the difference in gain between input levels of 65 dB SPL and 80 and 55 dB SPL). Therefore, we applied individual inverse filters for each subject. In terms of the gain spectra of Figure 5.1, this means that the amplification profile for the input level of 65 dB SPL was individualized for each subject and that the amplification profiles for 55 and 80 dB SPL were derived from that at 65 dB SPL, with the standard compression ratio from profile N3.

**Stimuli**

Stimuli were taken from the recorded VU98 lists and included single sentences with 0.5 s of noise before and after the sentences. The stimuli were presented monaurally with Sennheiser HDA200 headphones, which had been calibrated with a B&K Artificial Ear Type 4153. The noise level was 65 dB (A) (and the average speech level 69 dB(A) to realize an SNR of +4 dB) for stimuli in the unprocessed condition if no NAL-NL1 amplification was applied.

**Measurement procedure**

We used a similar detection task as that used in Chapter 2. In brief, all combinations of conditions required to answer our questions (Q2-Q4) were used in an oddball paradigm where the subjects’ task was to select from three stimuli which one sounded differently from the other two. Participants were allowed to listen to the fragments as often as they preferred before they responded. Directly after their responses, participants received a feedback on which stimulus was different from the other two.
In all, 15 distinct stimulus pairs were included (2 x 3 to answer Q2, 2 x 3 to answer Q3, and 3 to answer Q4), and each stimulus pair was tested thrice in AAB and thrice in BBA configuration to provide 90 trials per subject. This was divided in three separate blocks of 30 trials. The blocks alternated with two blocks of intelligibility measurement for Experiment 3.

5.3.2 Results

Figure 5.5 shows the group results divided over four panels for the separate (sub)questions of this experiment. Asterisks in the lower part of each panel indicate the detection rates that differed from chance level (33%) according to one-sided t-tests with Bonferroni correction for three comparisons.

![Figure 5.5](image-url)

**Figure 5.5:** Percentage of trials in which the odd stimulus was correctly identified for each combination of conditions and averaged for the 16 subjects. Each panel corresponds to one research (sub)question for this experiment. Error bars show 95% confidence intervals among subjects. Dashed horizontal lines show the chance level (33%). Asterisks indicate the combinations for which the detection rate was significantly higher than the chance level. Unpr: unprocessed, NR: noise reduction in a linear setting; C: compression; CNR: noise reduction in a compressive setting.
The upper panels show that the detection rate for combined processing compared with unprocessed within all three hearing aids was significantly higher than the chance rate (Q2a). Between hearing aids, the detection of differences in combined processing was above chance level for both combinations with CNR3, but not for the combination of CNR1 and CNR2 (Q2b).

To answer Q3, we compared the detection rate for NR with linear amplification (i.e., the difference between Unpr and NR; Figure 5.5, bottom left graph) with that for NR with compression (i.e., the difference between C and CNR; Figure 5.5, bottom left graph) for each hearing aid. This was done by using two-sided t-tests with Bonferroni correction for three comparisons. The detection percentages for the effect of noise reduction within a linear setting did not differ from those for noise reduction in a compressive setting within each hearing aid (uncorrected p-values: p = 0.04 for HA1, p = 0.20 for HA2, and p = 0.15 for HA3).

The bottom right panel shows that the participants could not differentiate between compression in the different hearing aids (all detection rates were at chance level).

5.3.3 Discussion

Combined processing of noise reduction and compression (Q2)

Q2a: Hearing-impaired listeners were able to distinguish combined noise reduction and compression processing (CNR) from unprocessed (i.e., linear amplification) in all the three hearing aids (see upper left panel in Figure 5.5). Thus, combined processing of noise reduction and compression changed the gain sufficiently to be audible. Detection percentages for the combined effect of noise reduction and compression were higher than those for the effect of noise reduction alone (Figure 5.5; percentages for Unpr-CNR in the top left panel were higher than those for Unpr-NR in the bottom left panel). These results agree well with the acoustical results from Experiment 1. Figure 5.3 shows that the CNR conditions changed speech and noise levels more than the NR conditions did. Note that higher detection percentages do not necessarily imply more benefit of the processing conditions. This will be investigated in Experiment 3.

Q2b: The results show that hearing-impaired listeners were able to distinguish between CNR conditions in different hearing aids. The upper right panel of Figure 5.5 indicates that the combined processing of noise reduction and compression (CNR) in HA3 could be distinguished from that in HA1 and HA2, which were not discernible from each other. The acoustical results (Figure 5.2) showed that CNR3 had a higher contrast between the lower (250-500 Hz) and higher (1000-2000 Hz) frequencies and that this did not change in the presence of speech. In contrast, CNR1 and CNR2 re-
resulted in a higher reduction in gain during the absence of speech. This may explain the higher detection rate for CNR3.

**Noise-reduction effect in linear and compressive aids (Q3)**

Hearing-impaired listeners could detect the effect of noise reduction equally well in linearly fitted hearing aids as in hearing aids fitted with compression (Figure 5.5, bottom left panel). Although this finding does not prove that the perceptual effect of noise reduction was the same in linear and compressive settings, it is plausible that compression did not influence noise reduction to a great extent, at least not in the hearing aids and conditions tested in this study.

**Detectability of differences in compression between the hearing aids (Q4)**

The subjects could not differentiate between compression processing in the three different hearing aids for the speech in noise signals that were used. Thus, for the current set of hearing aids, careful hearing aid fitting and inverse filtering achieved the removal of audible differences between compression in the hearing aids tested. This does not guarantee that it will work for all compressive hearing aids (see Chapter 2). The equalization filter cannot correct the differences in attack and release times, which may cause audible differences between hearing aids even if they are fitted with equal compression ratios. For instance, this could be the case for HA4 that was not included in the perceptual measurements but showed different compression characteristics compared with the other three hearing aids in Experiment 1 (Figure 5.2).

In the current study, the fact that the subjects could not detect differences between the three C conditions means that any perceptual differences that were found between the CNR conditions (see Figure 5.5 upper right panel and preference results in Experiment 3) can be attributed to the differences in either noise-reduction processing or interaction between noise reduction and compression.

### 5.4 Experiment 3: Perceptual effects

The final step in this study was to evaluate the combined effects of noise reduction and compression on speech intelligibility, noise annoyance, speech naturalness, and personal preference. Similar measurements were previously performed in Chapter 4 for the same hearing aids but with linear amplification (i.e., the three NR conditions were compared with each other and with the unprocessed condition). Here we evaluated the three CNR conditions, that were more representative of the application of noise reduction in the hearing aids. We compared the three CNR conditions with each other and with their joint reference condition “Unprocessed,” which was equal for all the three hearing aids. This is the same reference condition as that used in Chapter 4.
The research questions of Experiment 3 were as follows:

**Q5.** Does the combined processing of noise reduction and compression influence speech intelligibility in babble noise compared with (a) no processing (CNR compared with unprocessed within hearing aids) or compared with (b) the combined processing in other hearing aids (CNR compared between hearing aids)?

**Q6.** Does the combined processing of compression and noise reduction influence listeners’ preference (noise annoyance, speech naturalness, or overall preference) compared with (a) no processing (CNR compared with unprocessed within hearing aids) or compared with (b) the combined processing in other hearing aids (CNR compared between hearing aids)?

### 5.4.1 Methods

Measurements were done during the same visit as those for Experiment 2. Hearing aid recordings, subjects, stimuli, and amplification were the same as described before. We used recordings from four different hearing aid conditions: CNR conditions in HA1-HA3 and unprocessed condition in HA1, which did not perceptually differ from the unprocessed condition in the other two hearing aids (see Chapter 2).

**Intelligibility**

We measured the percentage of words correctly repeated by the subjects at a fixed input SNR of +4 dB for each condition. Each subject started with one list of 13 training sentences, containing all processing conditions. After this training list, we used two lists (test and retest) of 13 sentences per processing condition. Test and retest were separated by a block of 30 trials for the detection task (Experiment 2). We balanced the order of conditions across subjects to minimize the effects of training and fatigue on group data. We balanced the lists across conditions to minimize the effects of differences between lists. We considered the first 3 sentences of each condition as training sentences and used the last 10 sentences to calculate the percentage of correct words.

**Paired comparisons**

We used paired-comparison rating (a two-interval, seven-alternative forced choice paradigm) to measure noise annoyance, speech naturalness, and overall preference (see Chapter 3 for details). In brief, subjects listened to all the possible combinations of conditions and rated on a seven-point rating scale in which of the two conditions they found the speech to be more natural, in which of the two conditions they found the noise to be less annoying, and which of the two conditions they would prefer for prolonged listening. All subjects performed three runs of 6 comparisons, resulting in 18 comparisons per subject. All the subjects started with two training pairs.
5.4.2 Results

Intelligibility (Q5)

Figure 5.6 shows the percentage of words correctly repeated averaged over all the 16 subjects. For statistical analysis, we transformed these percentages to rationalized arcsine units (Studebaker 1985) and subsequently performed a repeated-measures analysis of variance (ANOVA) on the transformed data, with processing condition as the fixed effect. The effect of processing was not significant (p = 0.09).

![Figure 5.6: Mean and 95% confidence interval of the percentage of words correctly repeated by the subjects at an SNR of +4 dB. The scores for the four different conditions did not differ significantly from each other. Unpr is the unprocessed reference condition; CNR1, CNR2, and CNR3 are the conditions with noise reduction and compression in the three hearing aids tested.](image)

Paired Comparisons (Q6)

Figure 5.7 shows the average rating scores for each processing condition for the three criteria. We assigned scores from -3 to 3 for each condition, according to the ITU-T recommendation P.800 (1996). The scale for the noise annoyance is inverted in Figure 5.7 so that for each outcome a symbol plotted above the zero line means a better than average performance on that judgment criterion. For statistical analysis we used a log-linear modeling approach for ordinal paired comparisons described by Dittrich et al. (2004) in the same way as that described in Chapter 3. We performed a repeated-measures ANOVA on the worth parameters estimated with that model for each judgment criterion separately (noise annoyance, speech naturalness, and overall preference), with processing condition as the fixed effect. The effect of processing was significant for all the three judgment criteria (p < 0.001 for noise annoyance, p = 0.005 for speech naturalness, and p = 0.001 for the overall preference). Horizontal lines in Figure 5.7 indicate the processing conditions that differed significantly from each other in a pairwise comparison with Bonferroni correction for six comparisons.
5.4.3 Discussion

Intelligibility (Q5)

The combined processing of noise reduction and compression did not influence speech intelligibility at an SNR of +4 dB compared with no processing or combined processing in other hearing aids. The finding of no effect of noise reduction on intelligibility is common (Nordrum et al. 2006). Most other studies have compared noise reduction on and off within a compressive hearing aid (i.e., CNR vs. C), whereas we compared noise reduction and compression with linear amplification (CNR vs. Unprocessed). Chung (2007) made the same comparison as we did in two different hearing aids and also
found no difference in speech intelligibility scores between linear setting and combined processing of noise reduction and compression. However, one of those hearing aids slightly reduced intelligibility when compression was activated compared with linear processing (both without noise reduction). In that hearing aid, switching the noise reduction on in the compressive setting offset the negative effect of compression and brought intelligibility scores back to those of the linear condition. This demonstrates the difficulty in studying the interaction between compression and noise reduction. If Chung had only measured the effect of noise reduction in a compressive hearing aid, she would have found an improvement due to noise reduction. In fact, the underlying cause may just as well be that noise reduction undid the unfavorable gain alteration caused by compression.

In Chapter 4 intelligibility measurements were described for the unprocessed and NR conditions in the same hearing aids. We found in Chapter 4 that intelligibility slightly reduced for hearing aid HA2 due to noise reduction. In the current experiment, the CNR condition of the same hearing aid did not affect intelligibility. Thus, in combination with compression, noise reduction of HA2 seems less deteriorating for speech intelligibility than in combination with linear amplification. This is remarkable because although CNR2 had higher speech intelligibility, it reduced the speech level more than NR2 (Figure 5.3). This might be explained by Figure 5.2, which shows that the dynamic behavior also differed between CNR2 and NR2. Although CNR2 caused a relatively constant reduction in gain during speech (because noise reduction reduced gain mainly during noise and compression during speech for our stimuli), NR2 caused the gain to change quickly to reduce the noise during speech pauses while retaining the speech signal. Thus, in this particular hearing aid, it seems that the quick and rather large changes in gain caused by noise reduction during speech were more detrimental for speech intelligibility than a continuous moderate reduction in gain caused by noise reduction and compression combined.

**Noise annoyance, speech naturalness, and overall preference (Q6)**

Paired-comparison data showed that the combined processing of noise reduction and compression in HA1 and HA2 (CNR1 and CNR2) reduced noise annoyance compared with unprocessed and CNR3. CNR2 resulted in the strongest reduction in noise annoyance. Speech naturalness was lower for CNR3 than for the three other conditions, which was also observed for the overall preference.

The pattern for noise annoyance agreed well with that of the objectively determined reduction in noise level in Figure 5.3 (right panel, from CNR1 to CNR3). The results for noise annoyance were also comparable with those obtained in Chapter 4 for noise.
reduction in linear hearing aids (NR conditions of the same three hearing aids), except for HA3 in which noise reduction without compression (NR3) previously reduced noise annoyance but noise reduction with compression (CNR3) in the current experiment did not. This seemed to be inconsistent with the result from Experiment 1, where CNR3 reduced noise level more than NR3 (Figure 5.3). However, the negative judgments for speech naturalness and overall preference for CNR3 (Figure 5.7) show that its gain reduction (which was concentrated in the low frequencies; Figure 5.2) was perceived as unnatural. This unnaturalness may also have caused the subjects to judge the noise in this condition as more annoying.

Although the speech level was reduced in CNR1 and CNR2 (Figure 5.3), the subjects rated speech naturalness for these conditions not differently from unprocessed. However, the individual preference data suggest that subjects differed from each other in their opinion on speech naturalness. Some subjects rated speech naturalness for CNR1 and CNR2 higher than that for Unprocessed, whereas others did the opposite. Although there is no sufficient data for exhaustive analyses by dividing our subjects in groups based on their opinion on naturalness, these observations may form a basis for further investigations into individual differences in preference. In Chapter 3 we found that normal-hearing subjects differed from each other in whether they based their preference mainly on speech naturalness or on noise annoyance. The large individual differences in preference for noise-reduction strength between normal-hearing listeners found by Houben et al. (2012) support this hypothesis. The current findings also suggest the differences between hearing-impaired individuals, in whether they perceive processed speech as more natural (less noise) or less natural (more processing artifacts) than unprocessed speech. Although CNR1 and CNR2 decreased noise annoyance compared with unprocessed, they were not significantly preferred over unprocessed. Within the same hearing aids, significant preferences for NR1 and NR2 over unprocessed were found in Chapters 3 and 4, both for normally hearing and hearing-impaired listeners. Anderson et al. (2009) determined the preference scores for different configurations of compression and noise reduction and found that their NR condition was the most preferred. Their CNR conditions were even less preferred than unprocessed. However, compared with compression alone (C), the CNR conditions were more preferred. Comparable results were recently obtained by Wu and Stangl (2013) who determined the acceptable noise level (ANL) in different processing conditions. Subjects accepted less background noise in the compression condition (C) than unprocessed, but the activation of noise reduction offset this effect. Thus, the results on perceptual measurements with CNR highly depend on whether the reference condition is unprocessed or compressed. The positive effect of CNR is expected to be higher compared with compression than compared with unprocessed.
5.5 Conclusions

Acoustical analyses (Experiment 1) of hearing aid recordings of speech in babble noise with an input SNR of +4 dB showed that there are differences between hearing aids in terms of gain changes due to noise reduction, compression, and their combined processing. Combined processing of noise reduction and compression in the four hearing aids tested reduced both the speech and noise levels. This reduction due to combined processing was stronger than that for noise reduction or compression separately, indicating that both features do not cancel each other if combined for the hearing aids tested.

Experiment 2 showed that differences in processing within hearing aids were detectable for hearing-impaired listeners. Between hearing aids, the listeners could not detect differences in compression (C) condition; however, combined with noise reduction (CNR), the processing in one hearing aid was discernable from the other two.

The combined effect of noise reduction and compression did not influence speech intelligibility (Experiment 3). However, the combined processing reduced noise annoyance, which agreed with the reduction in noise levels found in Experiment 1. The reduction in speech levels found in Experiment 1 resulted in a reduction in speech naturalness only for one hearing aid (CNR3). That processing condition (CNR3) was less preferred than the other two and less preferred than unprocessed. Preference for CNR conditions relative to unprocessed seemed to be lower than previously found for the NR conditions, where processing of HA1 and HA2 were preferred over unprocessed. This indicates that the influence of compression should be considered for the development and evaluation of noise reduction algorithms for hearing aid application.