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A comparison of object-based and scene-based compression in virtual reality

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ABSTRACT

Despite technological advances, the main function of hearing aids remains sound amplification. To avoid overamplification, hearing aids use wide dynamic range compression (WDRC), which allows for controlling the amount of gain depending on the input sound level. As a side effect of these non-linear modifications, WDRC introduces undesired distortions, especially when applied to sound mixtures. In this study, we introduce an alternative approach, in which individual sound objects are separated prior to compression. Although the potential benefit of such processing has been discussed previously, perceptual evidence has not been investigated to date. We created a virtual reality (VR)-based listening experiment in which conventional, scene-based WDRC is compared with the proposed object-based WDRC, via measures of speech intelligibility, listening effort, comfort, and preference. Acoustic scene analysis is designed to capture the known detrimental effects of conventional WDRC: level fluctuations of the target signal interrupted by a competing masker; lack of adequate target gain; when the target signal is buried in noise; and decreased long-term signal-to-noise ratio (SNR) due to amplification of low-level background noise. Preference ratings and objective intelligibility scores indicated benefit and motivate further development of object-based approaches.

Keywords: Hearing Correction, Wide Dynamic-Range Compression, Virtual Reality

1 INTRODUCTION

Hearing loss is one of the most prevalent chronic health conditions in older adults. The World Health Organization estimates that by 2050 at least 700 million people will require hearing rehabilitation (7). Apart from the obvious perceptual consequences, unaddressed hearing loss may negatively impact cognitive, social, and economical aspects of life at the individual level. Although a universal cure for hearing impairment does not yet exist, assistive listening devices have demonstrated reduction of negative consequences (2, 26). Hearing aids help by capturing sound in listener’s surroundings and delivering the amplified acoustic signal to their ears.

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Hearing loss leads to reduced audibility of soft sounds, but it does not lower the sensitivity to loud sounds. On the contrary, reduced dynamic range of audible sounds increases susceptibility to changes in sound levels for people with hearing impairment (23). As a result, there are limits to the amount of amplification a hearing aid can provide while avoiding excessive amplification.

Use of input-level-dependent amplification (gain) rather than a fixed gain for all sounds is one of the fundamental principles of modern hearing correction. Current hearing aids are typically equipped with dynamic range compression (WDRC), which automatically adjusts gain based on input signal level. More gain is applied to low intensity sounds to improve audibility, and no or less gain is applied to high sounds to prevent uncomfortable and painful presentation levels.

When low or high intensity sounds appear in isolation, the appropriate amount of amplification can be provided with this approach. However, in many common acoustic environments, sound sources with different intensities are present at the same time. In such listening scenarios, WDRC acts on the superposed mixture signal captured by the microphone. This means that, most of the time, the function of the compressor is triggered by the loudest sound source present in the scene and the gain determined for this signal is applied to the whole mixture.

There are several detrimental effects related to applying dynamic range compression to the sound mixtures, which have been previously discussed in the literature (4, 5, 14, 21, 25). The first effect, here referred to as the *insufficient gain effect* occurs when a signal of interest has a lower intensity than a masking signal. In this case, the masker triggers WDRC and the resulting gain is lower than the gain that would be triggered by the target signal in isolation (See Fig. 2.A.). As a result, the target signal is not provided with a sufficient gain. The second effect, here called the *aggravated long-term signal-to-noise ratio (SNR) effect* occurs in conditions with low-level background noise. When higher-level target signals are not active, amplification is adjusted based on soft noise signals (See Fig. 2.B.). Even though the signal of interest is not influenced directly, the level of irrelevant information in the pauses is magnified, which in the long term can make the listening situation more challenging. The third effect, here termed the *fluctuating level effect* occurs when a signal of interest is occasionally interrupted with a higher intensity masker. The loud masker triggers the compressor which decreases the gain for the time during and shortly after the masker's activity. This causes fluctuations in the level of the target signal, which are especially perceivable for compressors with a long release-times as gain lags behind dynamic change of the envelope and cuts the onsets of lower-level target signals (See Fig. 2.C.).

The above discussed effects are caused because in conventional *scene-based* amplification the gain is determined jointly for all the sound sources in the mixture. Recent technological advances in the field of binaural source separation and spatial filtering (3, 8, 17) permit possibilities of alternative approaches in which the signals of individual sound objects are separated from the mixture prior to amplification (See Fig.1). The potential of these approaches in limiting detrimental effects of compression has been investigated previously. Corey and Singer (2017) showed that a multi-source compressor is less susceptible to noise and co-modulation effects than a conventional compressor. Despite encouraging results of the objective evaluations, the perceptual consequences of the *object-based* compression scheme have not been studied extensively so far.

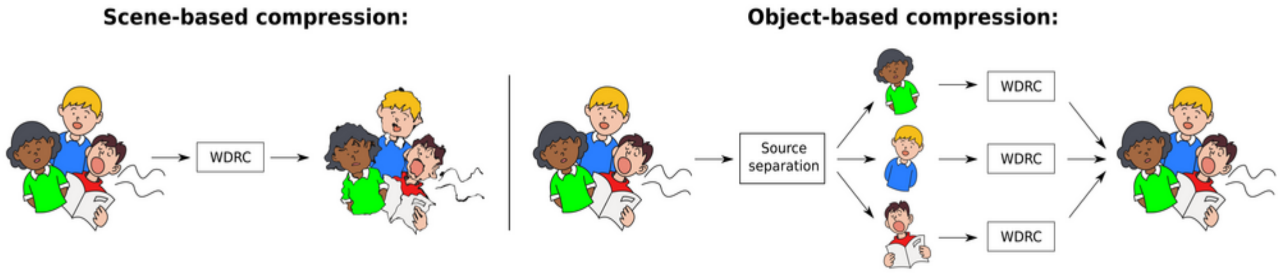


Figure 1: Illustration of the difference between the conventional scene-based compression and the investigated object-based compression. Figure inspired by (6).

The validity of perceptual studies related to hearing aid benefit has been revisited in several recent studies (12, 15, 22). The literature suggests consensus regarding the importance of addressing the aspect of ecological validity when designing listening experiments in the lab. Emerging virtual reality technologies are often mentioned as an approach to achieve a higher degree of realism in the lab (9, 11, 18). There are a few examples of studies adopting virtual reality in listening tests with hearing aids (10, 19, 20, 24).

This study contributes to understanding the potential real-life benefits and limitations of object-based amplification schemes in hearing devices. The aim of our listening experiments was to quantify the benefit of object-based compression with respect to scene-based compression in a simulated virtual reality environment. We assumed a perfect source separation and compared compression strategies in two listening experiments performed by participants with hearing impairment. Both experiments were performed in virtual reality using headphones, a head-mounted display, and contained stimuli for which the levels were chosen to reflect the three detrimental effects of the scene-based method detailed above. We measured objective intelligibility scores and subjective ratings of intelligibility, listening effort, willingness to listen and preference.

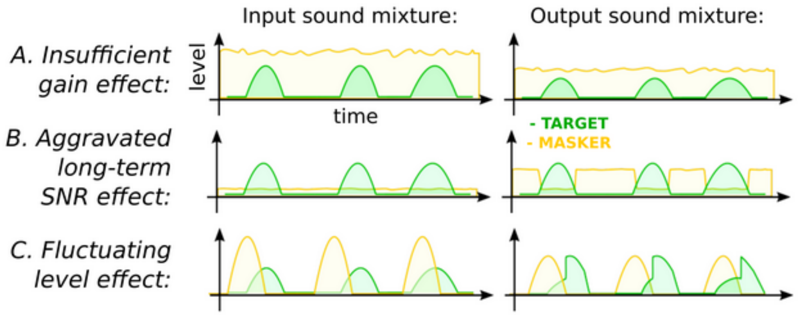


Figure 2: Schematic representation of three detrimental effects that might occur when applying WDRC to sound mixtures.

2 METHODS

2.1 Experiment A

Procedure:

The first experiment was designed to measure objective intelligibility scores in an acoustically controlled audio-visual scene using a balanced speech corpus. The procedure consisted of a training block followed by the experimental blocks. Each block consisted of 5 sentences from the Connected Speech Test (CST) corpus. The CST test is used to measure intelligibility of everyday speech and is intended primarily for quantifying hearing aid benefit (27). The test consists of 48 lists of connected sentences, each passage concerning a familiar topic. Sentences in each list become gradually specific.

The task of the participant is to repeat each sentence. At the end of the block, there was a questionnaire comprised of 3 questions: *1. How many words do you feel you recognized correctly?, 2. Approximately how long would you be willing to sustain listening in this scenario? 3. How much effort did you have to use to understand the sentences?* Each question had 5 possible ordered responses (See Fig. 3.A.).

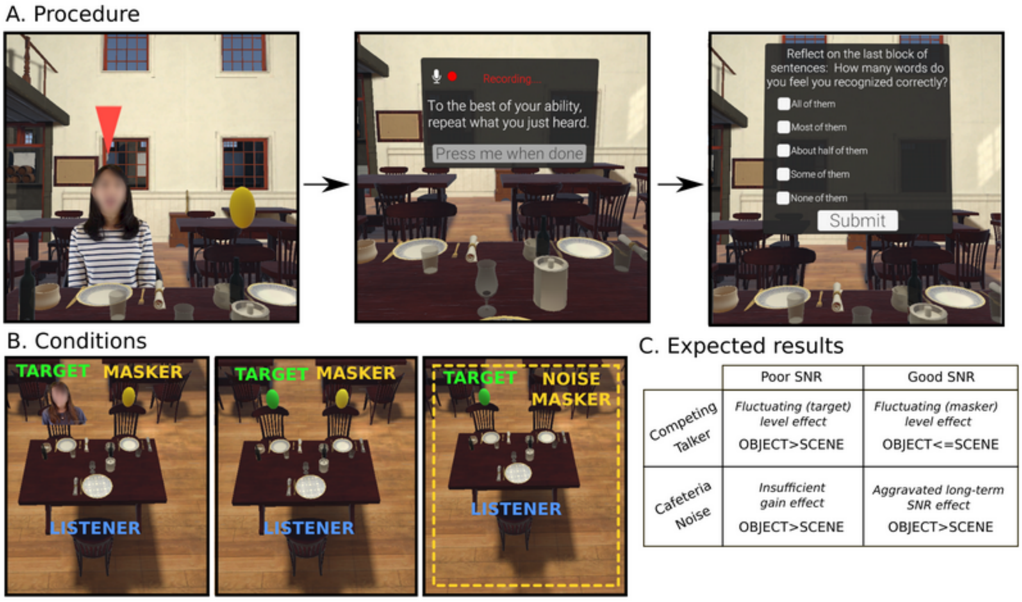
Intelligibility scores and self-reported ratings were collected in the following combinations of conditions: 2 WDRC strategies: object-based, scene-based, 2 interferer types: diffuse cafeteria background noise, competing talker, 2 different SNRs: -5dB SNR, +10 dB SNR, and 2 visual representations of the target talker: with lip-reading cues (video of a person), and without lip-reading cues (oval) (see Fig.3.B.) . In total there were 16 experimental conditions.

Conditions were randomized for each participant. We chose CST passages with average difficulty as determined in a preliminary experiment. Sentences were randomized across experimental conditions. Total test time was 15-20 minutes per participant.

Hypotheses:

The combinations of SNR and interferers were designed to reflect the 3 detrimental effects of the WDRC applied to the mixture (See Fig. 3.C.). Competing talker at poor SNR represented the *fluctuating level effect,* in which the interferer triggers compression an causes distortion in the lower-level target signal. In this condition we expected the object-based compression to provide benefit. Competing talker at good SNR represents the *fluctuating level effect*, however here the situation is flipped: the target signal triggers the compression and causes distortions in the interferer. In this condition we expected the object-based WDRC to lead to the same or worse results as the scene-based compression. Diffuse interferer at poor SNR represents the *insufficient gain effect.* We expected object-based WDRC to provide benefit as it applied more gain to the target signal than the scene-based WDRC. Diffuse interferer at good SNR represented the *aggravated long-term SNR effect.* We expected object-based compression to provide benefit as it did not amplify background noise in speech pauses. We additionally expected that the visual condition without lip-reading cues would demonstrate benefit of object-based compression.

2.2



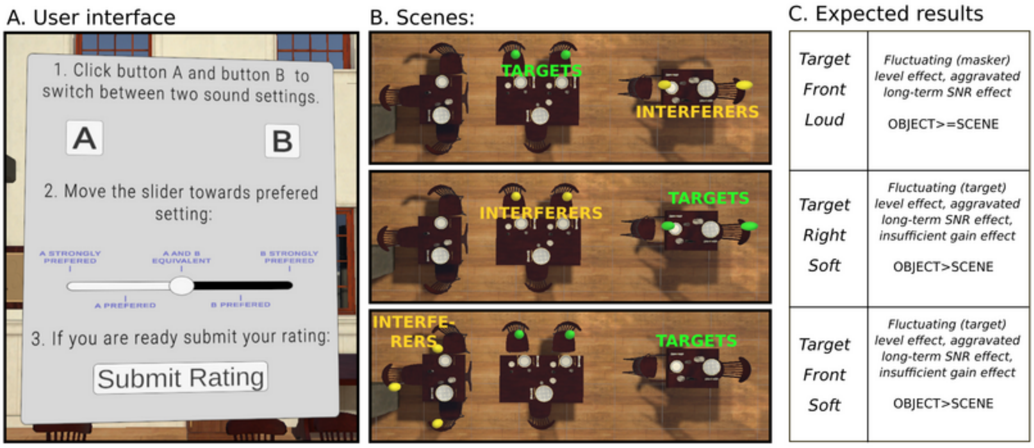
To the best of your ability, repeat what you just heard.

Reflect on the last block of sentences: How many words do you feel you recognized correctly?

☐ All of them
☐ Most of them
☐ About half of them
☐ Some of them
☐ None of them

	Poor SNR	Good SNR
Competing Talker	*Fluctuating (target) level effect* OBJECT>SCENE	*Fluctuating (masker) level effect* OBJECT<=SCENE
Cafeteria Noise	*Insufficient gain effect* OBJECT>SCENE	*Aggravated long-term SNR effect* OBJECT>SCENE

Figure 3: Experiment A: Speech intelligibility and subjective ratings with CST speech corpus.



1. Click button A and button B to switch between two sound settings.
2. Move the slider towards prefered setting:
3. If you are ready submit your rating:

Target Front Loud	*Fluctuating (masker) level effect, aggravated long-term SNR effect* OBJECT>=SCENE
Target Right Soft	*Fluctuating (target) level effect, aggravated long-term SNR effect, insufficient gain effect* OBJECT>SCENE
Target Front Soft	*Fluctuating (target) level effect, aggravated long-term SNR effect, insufficient gain effect* OBJECT>SCENE

Figure 4: Experiment B: Preference rating with natural conversations.

Experiment B

Procedure:

The second experiment was designed to capture the preference of the participants in a less acoustically controlled audio-visual scene with recorded natural conversations. The procedure consisted of a training scene, followed by 3 test scenes with simultaneous conversations. In each scene, participants were instructed to follow one conversation. Their task was to switch between two signal processing options (A and B) while following the conversation and when ready, submit their preference using a slider (See Fig. 4.A.). The slider offered discrete responses on a Likert scale. There were 3 test scenes, which differed in the arrangement of the target versus masker conversations: *Target Right Soft, Target Front Soft, Target Front Loud* (See Fig. 4.B.). After each scene there was a control multiple-choice question about the topic of the followed conversation. The level ratio between target and masker conversation was varied by placing them in different spatial locations of the scene. Each scene contained looped speech material of approximately 1-2 minutes in duration. A low-level cafeteria background noise was present in all scenes.

Hypotheses:

The scenes were designed to reflect the 3 detrimental effects of the WDRC applied to the mixture (See Fig. 4.C.). However, in contrast to Experiment A, in Experiment B we did not create a separate condition to reflect each effect. We were rather interested in measuring a cumulative influence of all potential effects on participants' preferences. In general, the *Target Right Front* scene and the *Target Front Soft* scene reflected a condition with a competing interferer at poor SNR, in which the *fluctuating level effect* is likely to occur, thus we expected preference for object-based WDRC. At times when the louder interfering conversation was very busy, we could have observed the *insufficient gain effect* in the scene-based WDRC, which could shift participants' preferences towards object-based WDRC. The *Target Front Loud* scenes reflects the condition with a competing interferer at good SNR, in which we expected the preference for the scene-based WDRC. All scenes contained low-level background noise responsible for the *aggravated long-term SNR effect*, which could shift preferences in favor of object-based WDRC.

2.3 Participants and WDRC presets

The amount of amplification in the WDRC had to be matched with the degree of hearing loss. To achieve this, we created 4 gain presets: N0, N1, N2, and N3. They were based on 4 standard audiograms (1) and the gain characteristics in each category were computed with the NAL-N2 procedure (16). A total of 27 participants with varying degrees of symmetrical hearing impairment were invited to take part in the study. participants were recruited using an online questionnaire. An audiogram was measured for each participant the day before the experiment. Based on the average hearing threshold from 1, 2, and 4 kHz, each participant was assigned to one gain preset group (<18=N0,18-28=N1,29-40=N2,41-60=N3). There were 2 participants in the N0 group, 15 participants in the N1 group, 3 participants in the N2 group, and 7 participants in the N3 group. In all groups, attack time was set to 10 ms and release time to 200 ms. Participants who used hearing aids were asked to remove them prior to the experiment.

2.4 Setup and equipment

Both experiments were performed using the Oculus Quest Headset connected with the Bayerdynamic DT 770 Pro Headphones. The audiovisual restaurant scene was created using Unity game engine. We used the Unity Experiment Framework open source package for data logging and control of the experimental procedure. For acoustic simulations we used the Oculus Spatializer Plugin for Unity, which implements head-movement dependent distance attenuation and HRTF-based spatialization. Room acoustics modeling was not included in the simulations. The recorded cafeteria noise was added in a first order ambisonics B-format. The two WDRC methods were implemented by importing the same C++-based DSP plugin at different sound processing stages of the Unity scene (See Fig. 5). For object-based WDRC, the plugin was applied at the level of the source, before spatialization; for scene-based WDRC, the plugin was applied at the level of the listener, after the mixing of the spatialized signals. Compression parameters were identical for both ears.

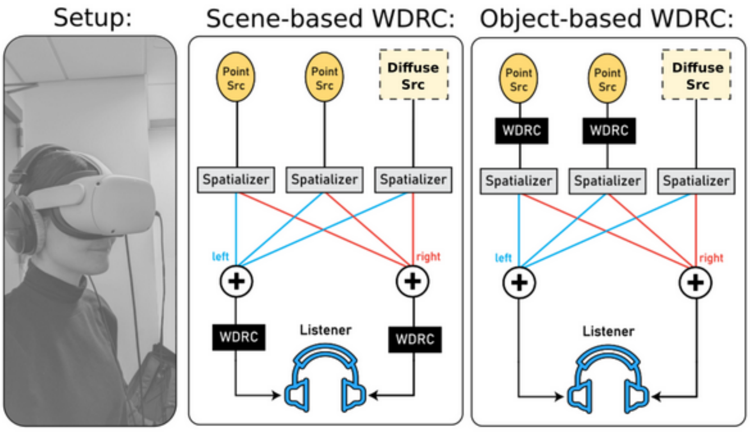


Figure 5: Setup (Oculus Quest 2 + headphones) and signal processing flow in Unity for object- and scene-based WDRC.

In Experiment A the playback system was calibrated using the KEMAR head and torso simulator. We determined the digital level of speech-shaped noise played back with the Quest 2 playback system at maximum volume which corresponds to 70 dB SPL headphone output. Speech-shaped noise was generated using the CST speech corpus and the physical level was computed by comparing the measured output with the 1 kHz Bruel&Kjar calibrator. The target level was kept constant and the level of the competing talker and diffuse noise maskers were varied to achieve the required SNR at the virtual listener.

In Experiment B the digital levels were adjusted manually at the maximum system volume to achieve naturally sounding scenes.

3 RESULTS

3.1 Experiment A

Scoring was conducted by counting the number of correctly identified words out of the total possible target words per sentence. Since words can only be correct or incorrect and the scoring is count-based, a binomial model was appropriate for analyzing the resulting data. The results of experiment A were analyzed using a hierarchical binomial model, which estimates the probability of correct word identification, under a Bayesian framework. Self-report ratings were collected with a 5-point ordinal response scale, so outcome data were best considered and modeled as ordered categorical (ordinal) responses. For these data, we constructed a hierarchical ordinal multiple regression model under a Bayesian framework.

Figure 6 presents the results for two interferer types at two SNRs for the WDRC conditions. We observed the expected tendency demonstrating benefit of object-based WDRC for most gain preset groups under competing talker and poor SNR conditions. However, significant performance differences were only observed for the N2 group without lip-reading cues. Object-based WDRC provided more benefit when no lip-reading cues available. There were no significant performance differences between object- and scene-based WDRC under competing talker and positive SNR conditions; most of the predicted responses were close to 100 %, which suggests participants encountered ceiling effects caused by insufficient difficulty in the speech stimuli at +10 dB SNR. Object-based WDRC tended toward to higher intelligibility for the N3 group, which conflicts with our initial hypothesis for this condition.

Our expectations were confirmed in the diffuse noise condition at poor SNR. We observed a significant benefit of object-based WDRC in 3 participant groups (N0, N2, N3). Although the tendency is visible for all groups, the results for the largest group of listeners (N1) were not considered significant.

Results for the diffuse interferer at high SNR were influenced by ceiling effects. The task in this condition may have been too easy to measure differences between WDRC strategies. Additionally, tendencies confirming the influence of SNR, and greater difficulty for the competing talker, and greater difficulty without lip-reading cues was observed. In contrast to the objective intelligibility scores, no clear tendencies confirming the advantage of object-based WDRC was observed in self-reported ratings.

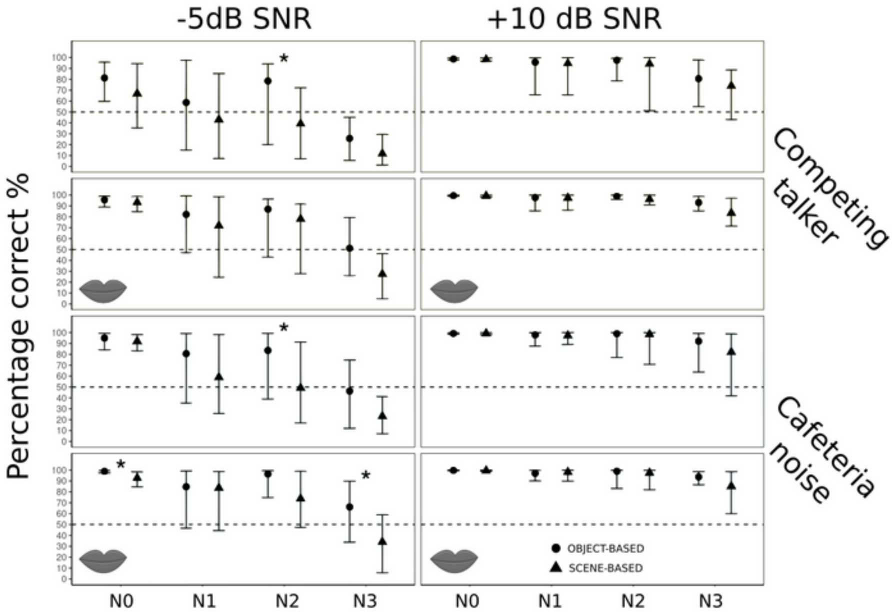


Figure 6: Results of intelligibility scoring in Experiment A. Points represent median probability of correct word recognition and error bars represent the 89% highest density credible interval surrounding the median values. Statistically significant differences between Scene and Object are marked with asterisks. Symbol of lips represents conditions with video of a person in which lip reading was possible.

3.2 Experiment B

Preference ratings in Experiment B were collected with a 5-point Likert response scale. A hierarchical ordinal multiple regression model under a Bayesian framework was used. The upper panel of Figure 7 plots raw counts of responses together with the predicted response counts from the model. The lower panel of Figure 7 plots aggregated responses, computed as a weighted sum of individual response probabilities, which can be interpreted as a measure of central tendency (similar to mean scores).

Object-based WDRC was slightly preferred by participants in the N1 and N2 groups. Participants in these groups preferred object-based WDRC in all scenes, but particularly in scenes where the interfering conversation was louder than the target conversation.

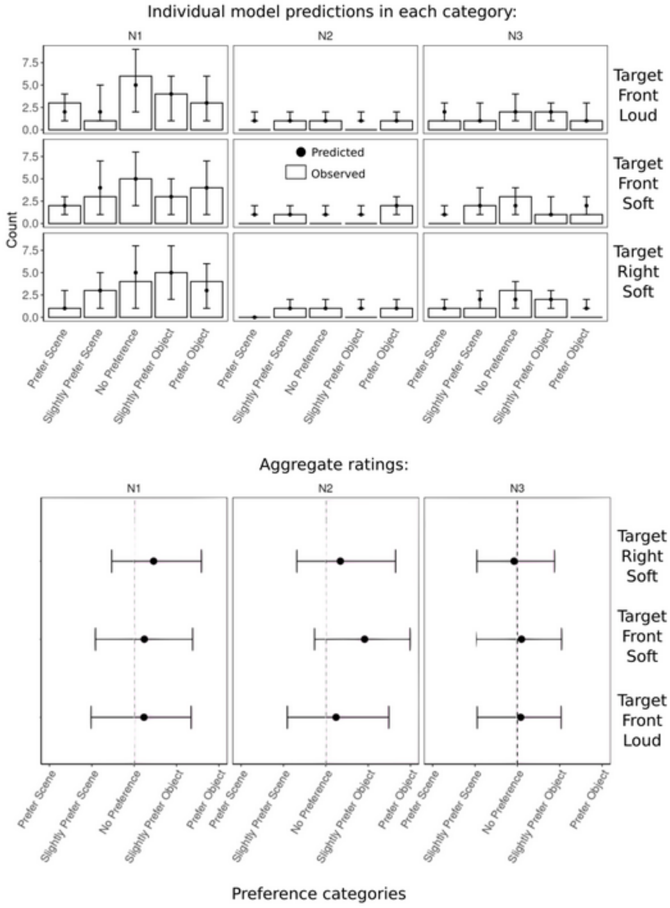


Figure 7: Results of preference rating in Experiment B. Upper panel plots counts of responses together with the predicted response counts from the model. Bars represent the observed quantity of each response category as a function of Scene. Points depict the median posterior predicted count and error bars depict the 89% highest density credible interval surrounding the median predicted counts. Lower panel plots aggregate ratings for each scene, which can be interpreted as mean scores. Points represent the median rating, error bars depict the 89% highest density credible interval.

DISCUSSION

The goal of the experiments presented in this study was to quantify the potential benefit of object-based WDRC. Objective scores in Experiment A showed promising results in favor of object-based WDRC. Results indicated that object-based WDRC improved speech intelligibility, especially in poor SNR, diffuse noise, and when visual cues were not present. Subjective ratings in Experiment B confirmed this advantage. In the Experiment B paradigm with a more realistic sound material and without lip-reading cues N1 and N2 participants tended to prefer object-based WDRC, especially in poor SNR. Conversely, subjective ratings in Experiment A did not align intelligibility scores. Participants reported no changes in intelligibility, listening effort, or willingness to listen. It is possible that the ratings failed to capture the differences between the methods because listeners rated the sound material after each block of 5 sentences independently. No direct comparisons between methods were made and participants may have changed their rating criteria throughout the experiment, depending on the topic of the list, for example. The advantage of object-based WDRC was not demonstrated in preference ratings in the N3 group. A larger effect was expected in this group because amplification had the strongest effect on the signal (this group had the most gain). The preference task required participants to simultaneously follow the conversation, switch between the signal processing strategies, and rate the sound material. Several participants found this task confusing. An additional aspect was the confusion of the spatial location of the sound sources with the spatial location of A/B switches in the user inferface. Another possible explanation is that N3 group participants found following the target conversation too difficult with either WDRC scheme, so they had no preference.

Our paradigm had several limitations. An important factor in the study design is the choice of the gain presets. Although gain presets were computed based on audiograms representing the most common hearing loss types, no personalization in the gain/frequency responses was used in these experiments. The degree to which individuals' hearing impairments were matched with the prescribed gain preset likely varied between participants bringing an additional source of variability in the data. Another limitation lies in the gain calculation methods between schemes. Object-based WDRC is computed based on the level of the signal at the source whereas in the gain of scene-based WDRC is computed based on the signal level at the listener. This could lead to lower gains applied in the object-based method and hence, an overall better audibility in the scene-based method. In this study we assumed perfect source separation prior to compression. In real-world scenarios the quality of source separation would certainly influence benefit from the object-based WDRC. Each source separation method may introduce specific artifacts, which could interact with non-linear amplification and should be investigated in further research.

Despite advances in technology and medicine, sound amplification remains the main strategy to address hearing loss. Limitations of conventional scene-based processing are likely one of the reasons why people with hearing difficulties leave their hearing aids at home. Although object-based amplification alone does not solve the dilemma of only amplifying desired sounds, the data presented in this work suggest that it can still provide benefit. While the results in diffuse noise reflect benefit from denoising (or the lack of noise amplification) and can be understood as a demonstration of the commonly known disadvantages of the scene-based processing, the results in competing talker conditions demonstrate benefit from object-based processing. Listening experience can potentially be improved by applying amplification separately to each source through object-based processing without knowledge of the desired source (intended speaker). These results can motivate development of object-based approaches prior to solving the complex desired-source detection problem.

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