Does amplitude compression help or hinder attentional neural speech tracking?

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Abstract

Amplitude compression is an indispensable feature of contemporary audio production and especially relevant in modern hearing aids. The cortical fate of amplitude-compressed speech signals is not well-studied, however, and may yield undesired side effects: We hypothesize that compressing the amplitude envelope of continuous speech reduces neural tracking. Yet, leveraging such 'compression side effect' on unwanted, distracting sounds could potentially support attentive listening if effectively reducing their neural tracking. Here we studied 24 normal-hearing (NH) and 9 hearing-impaired (HI) individuals who were asked to focus on one of two competing talkers while ignoring the other. Envelope compression (1:8 ratio, loudness-matched) was applied to one or both streams containing short speech repeats. Electroencephalography (EEG) allowed us to quantify the cortical response function and degree of speech tracking. With compression applied to the attended target stream, NH and HI participants showed reduced behavioural accuracy, and compressed speech yielded generally lowered metrics of neural tracking. Despite the expected weaker tracking of a compressed distractor stream, however, HI individuals exhibited stronger tracking of the concurrently presented target stream. Our results imply that intelligent compression algorithms, with variable compression ratios applied to separated sources, could help individuals with hearing loss suppress distraction in complex multi-talker environments.

Significant statement

Amplitude compression, integral in contemporary audio production and hearing aids, poses an underexplored cortical challenge. Compressing the amplitude envelope of continuous speech is hypothesized to diminish neural tracking. Yet, capitalizing on this 'compression side effect' for distracting sounds might enhance attentive listening. Studying 24 normal-hearing (NH) and 9 hearing-impaired (HI) individuals in dual-talker scenarios, we applied envelope compression to speech streams. Both NH and HI participants showed diminished neural tracking with compression on the speech streams. Despite weaker tracking of a compressed distractor, HI individuals exhibited stronger tracking of the concurrent target. This suggests that adaptive compression algorithms, employing variable ratios for distinct sources, could aid individuals with hearing loss in suppressing distractions in complex multi-talker environments.

Introduction

In everyday life, people often encounter challenging hearing situations where multiple auditory signals are present. Selective attention allows listeners to prioritise a target auditory signal over distracting signals that may be occurring simultaneously (Desimone & Duncan, 1995). People with normal hearing are remarkably adept at focusing on relevant signals (even complex signals like speech) while filtering out concurrent distraction (Cherry, 1953) . However, individuals even with mild to moderate hearing impairments often struggle in multi-talker situations. Hearing aids are the most common treatment for people suffering from hearing impairment.

In recent years, computational techniques have been developed to estimate neural responses to single continuous auditory stimuli, even in the presence of other sounds (Crosse et al., 2016) Electrophysiological responses in cortical regions phase-lock to speech features in magneto/electroencephalogram recordings (Luo & Poeppel, 2007). The "temporal response function" (TRF) captures this linear relationship between continuous speech features and neural response and can be interpreted in close analogy to the classical ERP(Crosse et al., 2016; Fiedler et al., 2019) Neural phase locking to the low-frequency envelope of speech, referred to as "neural speech tracking" (Obleser & Kayser, 2019), serves as an objective measure for differentiating attended speech from concurrently ignored speech. Numerous studies have shown that individuals with normal hearing exhibit stronger neural phase locking to the envelope of attended speech compared to ignored speech (e.g., Brodbeck & Simon, 2020; Ding & Simon, 2012; Fiedler et al., 2019; Zion Golumbic et al., 2013). Additionally, there is evidence that neural phase locking to the envelope of speech correlates with speech intelligibility(Peelle et al., 2013), as well as behavioural indices of speech comprehension(Etard & Reichenbach, 2019), and that stronger speech tracking enhances trial-to-trial behavioural performance (Kraus et al., 2021).

Since neural tracking can be an objective measure for selective attention and correlates with behavioural measures, it is an interesting basis for research concerning the hearing-impaired system. However, the literature provides mixed evidence on how hearing impairment affects the neural tracking of the speech envelope. Early studies showed that poorer hearing was related to stronger tracking of the ignored envelope (Petersen et al., 2017). On the other hand, more recent studies suggest that hearing-impaired listeners show stronger neural tracking

compared to the age-matched control group (Fuglsang et al., 2020). More recently, (Schmitt et al., 2022) reported enhanced speech tracking with increasing hearing loss and suggested that the hearing impaired rely more on the tracking of slow modulations in the speech signal to compensate for their hearing deficit. In contrast, other studies found no differences between older listeners with normal and impaired hearing in neural speech tracking (Goossens et al., 2019; Presacco et al., 2019) The contradictory effects of hearing loss on neural tracking may be due to the complex interplay between ageing, the severity of hearing loss, and cognitive abilities.

Neural tracking has been shown before to depend on acoustic signal processing. For instance, vocoding can lead to delayed neural separation of competing speech during attentional selection (Kraus et al., 2021) and late cortical tracking of ignored speech is modulated differently based on signal-to-noise ratios (Fiedler et al., 2019) Furthermore, a recent study found that neural speech tracking can serve as an indicator of the benefits of hearing aid algorithms, including amplitude compression (Petersen, 2022). Overall, these findings suggest that neural speech tracking could be a useful tool for researchers seeking to understand the effects of various hearing aid algorithms, such as dynamic range compression.

Dynamic range compression (DRC) is an audio signal processing algorithm that amplifies quiet sounds while reducing the intensity of loud sounds. Dynamic range compression is commonly used in hearing aids to compensate for loudness recruitment in hearing impaired listeners with presbyacusis and to restore the outer world audio dynamic into the listener's hearing range (Kates, 2005). However, dynamic range compression also leads to undesired side effects. For instance, compression directly affects the envelope of a speech signal. It reduces the amplitude modulation depth, and alters the envelope shape, and thus alters the intelligibility-relevant temporal cues contained in speech (Stone & Moore, 1992). The envelope of speech is thus not just a simple acoustic feature of speech but also associated with speech comprehension (Poeppel & Assaneo, 2020; Shetty, 2016).

The rationale of the present study is as follows: We first assume that dynamic range compression impairs, in general, the neural tracking of speech, which in itself is to be empirically shown. Top this end, we measured and modelled cortical brain responses to amplitude-compressed speech in normal and hearing-impaired listeners using EEG.

However, hearing aids can perform spatial signal processing. This allows hearing aids to apply different compression ratios to different spatial locations of signals (Best et al., 2021). If a comparable strong compression is only applied to ignored speech, this could be a potentially useful tool in a multi-talker situation. In addition to a pure reduction of the SNR, which has the consequence that ignored speech (noise) is very strongly down-regulated and makes a change of attention more difficult. In contrast, a higher compression ratio for ignored speech may provide a sweet spot between suppression and the ability to switch speakers situationally.

We here hypothesise that amplitude compression on an ignored speech stream will increase the neural separation between the attended and ignored streams. Behaviourally, this should lead to faster response times and increased behavioural responses. Behind hypothesis stands the rationale that compression on ignored talkers will reduce their salience and corroborate the listener's behavioural goal to attentionally suppress this stream.

To test our hypothesis, we first conducted a pilot experiment to determine the appropriate compression ratio for the following main experiments. We then recruited 24 normal hearing control participants to participate in a quasi-categorical paradigm in which the speech streams were either both unprocessed, both compressed, or only one of the two streams was compressed. As a control measure, we also modelled the human auditory peripheral response (auditory nerve response and envelope following response) using the model from (Verhulst et al., 2018) to investigate the peripheral fate of compressed and unprocessed speech in normal hearing and hearing-impaired participants. In the following, we measured 9 hearing-impaired participants with presbycusis in the same experiment as normal hearing participants, accounting for overall sound pressure level.

Methods

Participants

The participants in the current study were 24 young adults (18 female and 6 male), aged 18 to 34 (mean: 25.5). Each participant reported having a native language of German, having normal hearing, and having no prior neurological conditions. We measured pure tone audiometry between 250 and 4000 Hz (Figure 1) to confirm normal hearing. For the tested frequencies, all participants displayed auditory thresholds below 20 dB. We recruited a total of 12 participants with hearing loss, but three of them had to be excluded from the analysis. The first participant was excluded due to data loss during EEG recording, the second participant was excluded because they did not perform the task correctly, and the third participant was excluded because their hearing loss was due to acute causes in the right ear, rather than presbycusis. The study enrolled hearing impaired participants between the ages of 50 and 75 with mild to moderate presbycusis, defined as a pure tone average (PTA) between 20-50 dB HL (Humes et al., 2012) similar hearing thresholds in both ears with a maximum difference of 10 dB, and no or less previous experience with compression in hearing aids, either unaided or with no longer than one year of prior use. The remaining N = 9 participants were aged between 60 to 75 years old, with an average age of 68.4 years. This also means that both groups were not matched in age. To assess their hearing ability, pure tone audiometry was also performed for frequencies ranging from 250 to 4000 Hz (Figure 1).

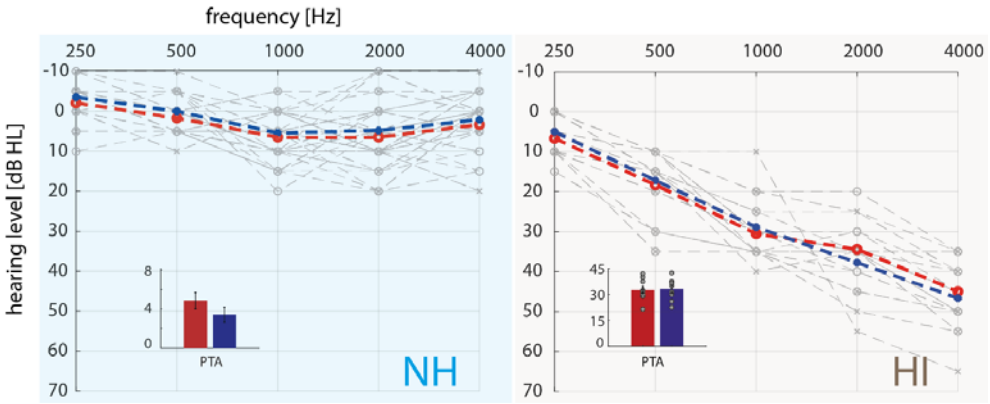

Figure 1. Pure tone audiometry. Left: Normal hearing participants (NH, N = 24). Right: Hearing-impaired participants (HI). Average pure tone hearing thresholds of the left (blue cross) and right (red circle) ear across frequencies (250 -4000 Hz) for N = 9 hearing-impaired participants. Grey lines show single-subject hearing thresholds (left-cross; right-circle). Inset shows pure tone average (PTA); bars indicate the mean ± standard error, grey dots indicate single-subject data.

All participants showed the typical sloping progression to higher frequencies in auditory thresholds, with pure tone averages ranging from 22-42 dB HL and an average of 32.6 right and 33.2 left dB HL. They provided written, fully informed consent and were paid 10 euros per hour. The study was approved by the local ethics committee of the University of Lübeck.

Stimulus materials

We presented audio versions of two different narrated book texts, "Ludwig van Beethoven Basiswissen" and "Sophie und Hans Scholl Basiswissen", both of which were spoken by professional talkers. We selected audio streams that had not previously undergone amplitude compression. At an average intensity (SPL mixture) of about 65 dB(A), which is comparable to the volume of a normal conversation, the two audio streams overlapped in time.

Using customised MATLAB code, the stimuli were processed in the following steps (Version 2018a Mathworks Inc., Natick, MA, United States). The audio files had a 44.1 kHz sampling rate and a 16-bit resolution. The maximum duration of silent periods was reduced to 500 ms (O'Sullivan et al., 2015).

By selecting 400 ms of the original audio stream and repeating it immediately after, we added brief repeats to both audio streams(Marinato & Baldauf, 2019; Orf et al., 2023). At least two seconds after the stimulus began, the first repeat was shown. By linear ramping and cross-fading, each repeat was incorporated into the sound stream. Utilizing a window of 220 samples (5 ms) from the down ramp's end and the first 220 samples (5 ms) from the repeat itself, linear ramping was performed (up ramp). The cross-fading was accomplished by combining the up and down ramps.

In order to prevent undetectable repeats of weak sound intensity, we further used an rms (root mean square) criterion, which required that the repeat's rms be at least equal to the rms of the stream from which it was drawn (Orf et al., 2023).

Using a digital dynamic range compressor built into MATLAB, we applied amplitude compression to the speech streams (Giannoulis et al., 2012). The following is how we set the compressor parameter:

Attack time: 2 ms; release time: 15 ms; threshold: -40 dB. We used a high compression ratio and relatively quick attack and release times compared to standard

hearing aid processing (e.g., Kates, 2005). Then, to avoid clipping, the uncompressed and compressed audio books were both limited to 99.95% The compression ratio was determined by a pilot experiment (Figure 2A).

We created four pairs of segments -uncompressed & uncompressed, uncompressed & compressed, compressed & uncompressed, and compressed & compressed- each belonging to both streams that were simultaneously presented to maintain a balance between compressed and uncompressed segments in the two streams. Each pair had a duration of 5-minutes. The pairings were arranged in a balanced and random manner (Figure 2B).

The root-mean-square (RMS) is frequently used to match the intensity of distinct audiobooks. However, it was demonstrated that the perceived loudness of RMS matched unprocessed and compressed speech differs (B. C. J. Moore et al., 2003) Here, we matched the perceived loudness for time-varying acoustic signals based on Zwicker using an internal MATLAB function (Zwicker & Scharf, 1965)

We conducted a psychophysical experiment to confirm the viability of this algorithm using the stimuli we had previously used. The results suggest no significant differences in loudness perception between uncompressed and Zwicker matched compressed speech.

The cue was presented at the center of the screen (resolution: 1920x1080, Portable HDMI Screen, Wimaxit) in front of the participant (distance: 1 m). The spatial cue consisted of two sub-triangles which had a size of 1.3° visual angle pointing to the front and back sound sources The two triangles had different colours blue and red. Participants had to attend either to the red or the blue triangle. Since the cue and the fixation cross were presented at the same time as the auditory stimuli, we ensured that the possible interference between visual and auditory neural responses was as small as possible. In order to achieve this, the cue was linearly faded in and out (50 ms each) to create a seamless transition between the fixation cross and cue.

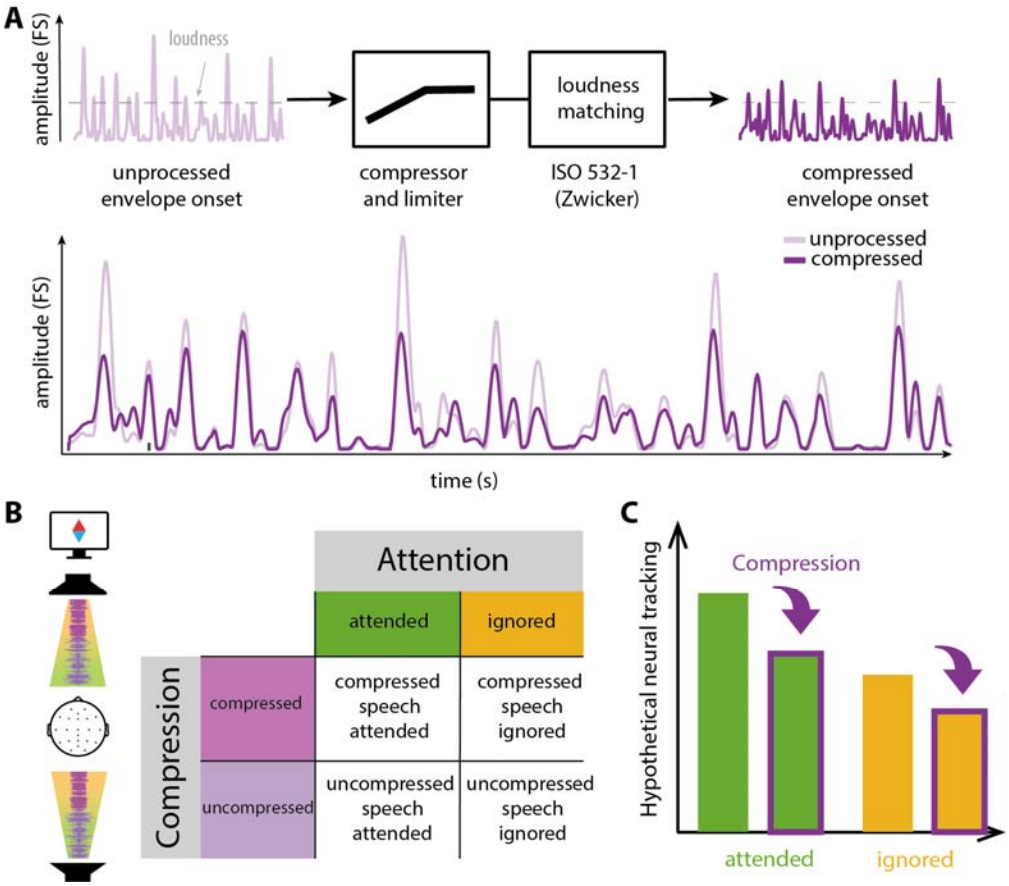

Figure 2. Stimulus processing, experimental design and hypothetical results. The most important stimulus processing flow is shown by **A**. The stimulus is expressed as the envelope onset of the speech signal. First, the signal is processed by the compressor (ratio: 1/8, attack time: 2 ms; release time: 15 ms; threshold: -40 dB). Importantly, the limiter was then applied to both signals the uncompressed and compressed signals- to avoid clipping. The compressed audio segments were matched to the loudness of their uncompressed counterparts by using a MATLAB algorithm based on Zwicker **B**. Left: Experimental setup. Two loudspeakers are placed in front (0°) and back (180°) of the participant. Speech streams are simultaneously presented over both loudspeakers. A screen was placed in front of the participant. A spatial cue indicated to which location participant had to attend. Right: Experimental paradigm. We had a quasi-factorial design with the factors attention (2- levels: attended and ignored) and compression (2-levels: compressed and uncompressed). Importantly, attending and ignoring always happened at the same time, while the factor compression was fully balanced. **C** Hypothetical results. For the main effects, we would expect that attention (to-be-attend to the cued stream) has a positive effect on the dependent variables, which means that attention leads to increased behavioural and neural results. In contrast, compression would have a negative effect on the dependent variables, that is, decreased neural and behavioural results.

Experimental Setup

The experiment was conducted in a soundproof chamber with two loudspeakers (Genelec: Speaker 8020D, Denmark) placed at a one-meter radius in the front and back. The ground was 1.20 meters away from the loudspeakers, and a chair was positioned in the center of the radial speaker array with its face aligned to the loudspeaker at position 0° in the azimuth plane (Figure 2B). Participants received a briefing on the experiment in advance. Each participant was instructed to keep their eyes open, keep their gaze on the center of the screen, and sit as comfortably as they could. A chin rest was utilized to prevent head movement. Each participant had their chin rest adjusted in height.

Experimental Procedure

To study amplitude compression in a competing-talker paradigm, we developed a new experimental procedure. The experiment was created using Psychophysics Toolbox extensions (Brainard, 1997) and MATLAB (MathWorks, Natick, MA, USA). Two audio streams were played simultaneously for participants. Each trial started with a cue that specified which stream to attend, displayed for 500 milliseconds. A fixation cross was then shown for the remainder of the trial (19.5 s), while the auditory stimuli continued to play in the background. Trials were presented continuously, with the next trial starting immediately after the previous one ended.

Participants were required to identify short repeats in the target stream, with six repeats included in each trial and randomly divided between the two streams. Prior to data collection, the experiment was explained to participants, emphasising the importance of listening to the target stream's content and responding as quickly and accurately as possible to a repeat. Participants were given a single sentence containing one repeat to acquaint them with the repeats and were asked to provide oral feedback if they were able to recognise it. Additionally, participants completed six practice trials that were identical to the main experiment but used different audio streams. The main experiment lasted approximately one hour and included 196 consecutive trials split into four blocks, with participants having the opportunity to rest between each block.

Sound pressure level adjustments for hearing-impaired participants

The hearing-impaired participants completed the same experiment as their normal hearing counterparts, using the same stimuli but with different randomizations of conditions. However, we made one change: We adjusted the overall

sound pressure level of the experiment based on each participant's hearing loss. To determine their hearing threshold, we used 500 ms parts of the stimuli that were presented in the experiment itself over free-field loudspeakers. We employed a combination of limit and constant stimuli methods to establish the threshold for the experimental stimuli. First, we presented pairs of compressed and uncompressed stimuli snippets (one over the front loudspeaker, one over the back), with one always louder than the other. In 3 dB steps, we decreased the sound pressure level of the signals each time the participant pressed a button to indicate they could hear the sound snippet. Once the participant stopped responding, we set this level as a reference for the method of constant stimuli. We then presented three different levels in 2 dB steps before and after the reference level, with each level presented 10 times in random order for a total of 70 presentations. We used the participants' responses to fit a psychometric function and obtained the SRT50 of this function as the new determined threshold. We added 35 dB to this threshold to set the presentation level. However, we asked each participant after the procedure if the overall presentation level was appropriate for them. If they did not agree, we adjusted the presentation level in 5 dB steps until it matched their reported most comfortable perceived loudness. On average, the presentation level was 72 dB ranging from 65 to 88 dB SPL.

Data acquisition and pre-processing

A 24 electrode EEG-cap (Easycap, Herrsching, Germany; Ag-AgCl electrodes positioned in accordance with the 10-20 International System) connected to a SMARTING amp was used to record the EEG (mBrainTrain, Belgrade, Serbia). The portable EEG system sends the signal via Bluetooth to a computer for recording. Using the program Smarting Streamer (mBrainTrain, version: 3.4.2), EEG activity was captured at a sample rate of 500 Hz. Impedances were kept under 20 kΩ while impedances were used as an online reference during recording using electrode FCz. The Fieldtrip-toolbox, built-in functions, and MATLAB (Version 2018a Mathworks Inc., Natick, MA, United States) were used for offline EEG preprocessing (Oostenveld et al., 2011). High- and low-pass filters were applied to the EEG data between 1 and 100 Hz, and the electrodes M1 and M2 (the left and right mastoids) were averaged (two-pass Hamming window, FIR). On the EEG data from every participant, an independent component analysis (ICA) was performed.

Prior to ICA, M1 and M2 were removed. Visual inspection was used to identify and remove ICA components associated with eye blinks, eye movement, muscle noise, channel noise, and line noise. On average, 7.89 out of 22 components (SD = 2.74), were disqualified. Back projected to the data were elements not connected to artifacts. Clean EEG data were processed further. Frequencies up to 8 Hz are associated with neural speech tracking (Luo & Poeppel, 2007). EEG data were therefore low-pass filtered once more at 10 Hz (two-pass Hamming window, FIR). EEG data were then segmented into epochs that matched the trial length of 20s and resampled to 125 Hz.

Extracting the speech envelope

By calculating the onset envelope of each audio stream, the temporal fluctuations of speech were quantified (Fiedler et al., 2017). In the beginning, we used the NSL toolbox (Chi et al., 2005) to compute an auditory spectrogram (128 sub-band envelopes logarithmically spaced between 90 and 4000 Hz).

To create a broad temporal envelope, the auditory spectrogram was secondly averaged across frequencies. Third, the half-wave rectified first derivative of the onset envelope was obtained by computing the first derivative of this envelope and zeroing negative values. In order to match the EEG analysis's target sampling rate, the onset envelope was lastly down sampled (125 Hz). By using the onset envelope instead of the envelope, the envelope is moved in time. It's significant that the TRF obtained by using the onset envelope as a regressor resembles a conventional ERP the most(Fiedler et al., 2017).

Temporal response function and neural tracking estimation

A temporal response function (TRF) is a condensed brain model that illustrates how the brain would process the acoustic speech envelope of the stimulus to produce the recorded EEG signal if it were a linear filter. To calculate the TRF, we employed a multiple linear regression method (Crosse et al., 2016). In order to more precisely predict the recorded EEG response, we trained a forward model using the onset envelopes of the attended and ignored streams (e.g., Fiedler et al., 2019) In this framework, we examined delays between envelope changes and brain responses of between -100 and +500 ms.

To address EEG variance related to processing behaviourally relevant repeats and corresponding evoked responses, we added all repeat onsets and button

presses as nuisance regressors using stick functions. These repeat onsets were added independently of the speech envelope regressors and chosen almost randomly (within SNR threshold) for each speech stream.

To prevent overfitting, we used ridge regression to estimate the TRF and determined the optimal ridge parameter through leave-one-out cross-validation for each participant. We predefined a range of ridge values, calculated a separate model for each value, and averaged over trials to predict the neural response for each test set. The ridge parameter with the lowest mean squared error (MSE) was selected as the optimal value specific to each subject. TRFs were estimated from trials in the experiment. To avoid cue conflicts, the first second of each trial was excluded. One model was trained on 192 trials using predictor variables for the onset envelopes of attended and ignored streams, as well as stick functions for repeats and button presses. These were modelled jointly (same regressor matrix) using the same regularization.

Neural tracking measures the representation of a single stream in the EEG signal, using TRFs to predict the EEG response. By using Pearson correlation to compare the predicted and actual EEG responses, the neural tracking (r) was calculated. By using the leave-one-out cross-validation method, we were able to predict the EEG signal on single trials (see above). A sliding-time window (48ms, 6 samples, 24ms overlap) calculated neural tracking accuracy over TRF time lags, resulting in a time-resolved neural tracking (Fiedler et al., 2019; Hausfeld et al., 2018; Kraus et al., 2021; O'Sullivan et al., 2015).

Peripheral auditory modelling

We employed a computational model of the human auditory periphery developed by Verhulst and colleagues al. (2018) to simulate model outputs to the speech signals used in our experiments presented at 65 dB SPL. We randomly selected 100 speech snippets from our uncompressed stimulus material and applied the same processing pipeline (including compression and loudness matching) as used in our main experiment to create a set of 100 compressed speech snippets and a corresponding set of 100 uncompressed snippets. We modelled the firing rate of the auditory nerve (AN) and the envelope following response (EFR) for both normal hearing and hearing-impaired participants, simulating a typical mild to-moderate presbycusis (hearing loss due to aging) starting at 1 kHz and sloping to 35 dB HL at 8 kHz. As the AN response varies with frequency, we focused on

four center frequencies (500, 1000, 2000, and 4000 Hz) that are particularly relevant to speech in audiology (Sweetow & Silverman, 1994). The EFR, which reflects the neural processing of the temporal envelope, was modelled without frequency dependence.

To analyse the output of the auditory nerve (AN) in greater detail, we employed a mixed model. The dependent variable was the log-transformed spike rate of the modelled AN. We used the same speech snippet to generate both uncompressed and compressed outputs, for both normal hearing (NH) and hearing-impaired (HI) conditions, resulting in four different AN output for each speech snippet. To account for the quasi-repeated measures nature of the data, we included speech snippet as a random effect in the mixed model. In addition to hearing impairment (NH, HI) and signal manipulation (uncompressed, compressed), we also included frequency (500, 1000, 2000, and 4000 Hz) as a factor in the model.

Statistical analysis

We employed various statistical methods to address our research questions. To examine the behavioural data in relation to detected repeats, we utilised logistic regression to model the binary outcome (hit = 1/miss = 0) of each repeat. We used a mixed model to predict the continuous dependent variable response speed. We incorporated both attention and compression categorical predictors in both models to examine their main effects and interactions. To investigate the attentional pairs (separate model), we incorporated a categorical predictor that indicated the corresponding information of the pair in which the dependent variable was measured. To assess statistical differences in neural tracking, we employed mixed models with the same categorical predictors as previously mentioned. However, the difference was that we utilised the models to predict neural tracking. Additionally, we included the categorical predictor space (front/back) to control the spatial assignment of loudspeakers in the setup for all models. We used jamovi for, gamlj package in R for fitting generalized linear mixed models (Jamovi Project, 2020), and MATLAB's fitlme function for fitting linear mixed models (MathWorks Inc., 2020).

Statistical analysis on time series

We investigated whether there were differences in time points in time-resolved neural tracking and TRF between subjects in different conditions and attentional pairs. To do this, we utilized a two-level statistical analysis known as cluster per-

mutation test, which was implemented in Fieldtrip (Oostenveld et al., 2011). The analysis was conducted on data from 22 channels. At the single-subject level, we performed one sample t-tests to assess TRF and time-resolved neural tracking differences. Clusters were defined based on resulting t-values and a threshold set at $p < 0.05$ for at least three neighbouring electrodes. The observed clusters were compared to 5000 randomly generated clusters through a permutation distribution using the Monte Carlo method to correct for multiple comparisons (Maris & Oostenveld, 2007). The cluster p-value was determined by the relative number of Monte Carlo iterations in which the summed t-statistic of the observed cluster exceeded that of the random clusters.

Due to the small sample size of only nine participants with hearing impairment and six participants for the pilot study, we employed double iterative bootstrapping to assess the statistical significance of our results. This method is particularly useful for small sample sizes and can help to mitigate issues with low power and unreliable results. Double iterative bootstrapping involves resampling both the participants and the data, and then running the analysis multiple times to generate a distribution of results that can be used to estimate the true population parameters. Instead of using a single bootstrap, we opted for a double bootstrap approach(Fox, 2015) to improve the accuracy of the confidence intervals. We performed the bootstrap procedure using the iboot package, which is designed for iterated bootstrap analysis of small samples and samples with complex dependence structures. We implemented the procedure in Matlab (MathWorks Inc., 2020) and used 2000 bootstrap samples and 200 repetitions for the inner loop based on the methods of (Efron & Tibshirani, 1993) and (Fox, 2015).

Results

The effects of compression ratio on neural tracking of speech

In this pilot experiment, six young individuals with normal hearing were asked to listen to a narrative story that contained randomly balanced parts of three different compression and expansion ratios. The compression ratios were 1:2 and 1:8, while the expansion ratio was 2:1. The participants were also presented with a baseline condition where the narrative story was unprocessed. The task was to listen to the content of the presented narrative story. The objective of this pilot experiment was to identify an appropriate compression ratio to be used in a follow-up study.

For this pilot study, we opted to use a decoding approach rather than an encoding approach. The main reason for this choice was to take advantage of the higher accuracy that can be achieved by using all EEG channels for reconstruction also given the small sample. Additionally, we were able to avoid potential confounds related to the temporal response functions of the brain to repeated stimuli, as well as confounds related to button presses since repeats were not included in this pilot experiment.

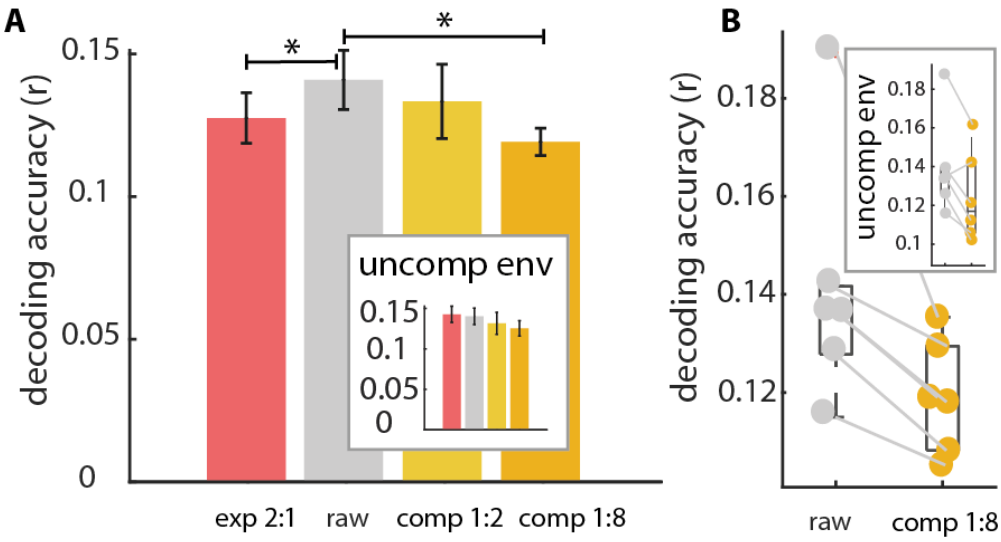

Figure 3. Neural results for different compression and expansion ratios. A. Decoding accuracy refers to the Pearson correlation between the stimulus onset envelope and the estimated onset envelope, using all EEG channels. Inset: shows the decoding accuracy obtained by using the uncompressed onset envelops for all conditions. Bar plots indicate the participants' means, and error bars indicate the standard error of the mean (SEM). **B** This plot shows the decoding accuracy for the unprocessed baseline compared to the 1:8 compression ratio, with dots representing individual subject data and connection lines indicating the same subjects. Inset: shows the decoding accuracy obtained by using the uncompressed onset envelops for all conditions. The boxes represent the interquartile range (25th to 75th percentile) of the data, with the median indicated by a line inside the box. The whiskers extend to the most extreme data point, excluding outliers.

Figure 3 A depict the averaged decoding accuracy for different compression and expansion ratios. To investigate differences between conditions we used bootstrapped CIs. For the comparison of compression ratio 1:2 and expansion ratio 2:1 versus unprocessed baseline (raw) the bootstrapped CI included zero, indicating a non-significant difference. However, for the difference between compression ratio 1:8 and raw the bootstrapped CI is not including zero, indicating a significant difference. That is, the decoding accuracy for the 1:8 compression ratio was significantly lower than that for the unprocessed speech, as indicated by a bootstrap CI that did not include zero. Interestingly, each participant shows a decreased decoding accuracy for the 1:8 compressed speech signal (Figure 3B).

In all our analysis, we used the onset envelopes of the actually presented signals. As a control, we also conducted an analysis using the uncompressed onset envelope, even when the signal was expanded or compressed, while keeping the ridge regression parameter λ constant (Figure 3A Inset). In this alternative analysis, we observed that most (5 out of 6) participants demonstrated a decrease in neural tracking, as measured by decoding accuracy, for compressed (1:8) speech (Figure 3 B Inset).

Based on the results of the pilot experiment, we concluded that using a 1:8 compression ratio for amplitude compression reduces the brain's ability to track speech. Therefore, we chose to use this compression ratio in our main experiment, which also included attention as an experimental factor. We made this decision for two main reasons. Firstly, our initial hypothesis that compression on ignored streams would increase neural separation only works when participants focus their attention on one stream and ignore the other. Secondly, attention could also have affected the compression effect in the pilot experiment, as participants may not have been attending to the compressed (1:8) speech stream.

The interplay between dynamic range compression and selective attention in normal hearing and hearing-impaired listeners

24 young, hearing-normal participants and 9 hearing-impaired were simultaneously presented with two streams of continuously narrated audio. The assignment of amplitude compression to the speech streams was counterbalanced within participants. They had to alternate between the two audio streams on a trial-by-trial basis. Participants had to identify any repetitions quickly and accurately in the attended stream while ignoring the unattended stream.

Amplitude compression impairs participants performance

Here, we analysed the behavioural data in terms of the proportion of detected repeats and response speed (Figure 4). For the main effects, we would expect that attention (to-be-attend to the cued stream) has a positive effect on the dependent variables, which means that attention leads to an increased proportion of detected repeats and an increased response speed (inverse of response time). In contrast, compression would have a negative effect on behaviour, that is, a decreased proportion of detected repeats and a decreased response speed. In addition, we would expect that the effect of attention depends on compression, with compression on the ignored stream increasing behavioural performance in con-

trast to the attentional pair where no compression is applied to the ignored stream.

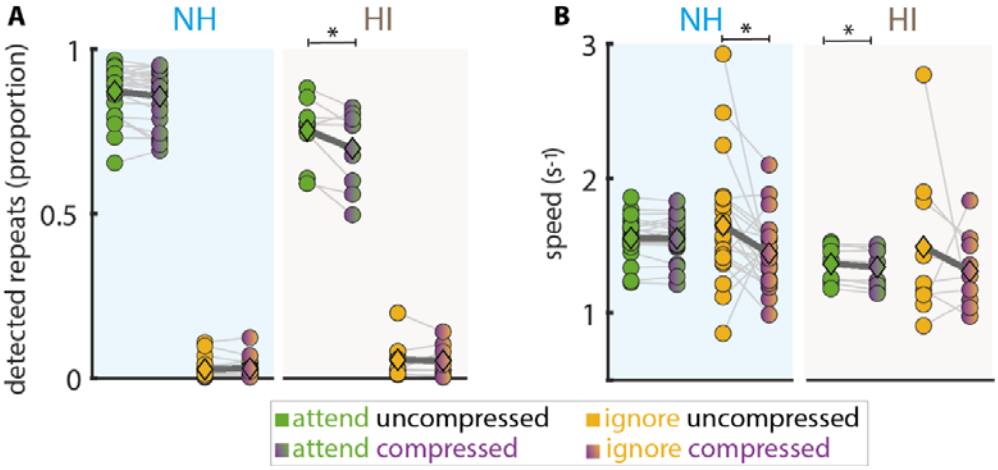

Figure 4. Proportion of detected repeats and corresponding response speed. **A** Left: Proportion of detected repeats per condition. Dots show individual NH (N=24, blue) and HI (N=9, brown) mean proportions of detected repeats. Light grey lines indicate the same subject. The bold line represents the mean of the group. Green dots indicate attend tracking, while orange dots indicate ignored tracking. Purple colour indicates compression. **B** Response speed per condition. Dots show individual (N=24, blue) and HI (N=9, brown) mean response speed. Light grey lines indicate the same subject. The bold line represents the mean of the group. Green dots indicate attend tracking, while orange dots indicate ignored tracking. Purple colour indicates compression.

NH participants were well able to detect repeats in the attended uncompressed stream (Figure 4 A left; mean accuracy: 0.87, 95% CI: [0.84, 0.90]; mean speed: 1.56 s^{-1}, 95% CI: [1.49, 1.62 s^{-1}]). They were also well able to detect repeats in attended compressed stream (mean accuracy: 0.86, 95% CI: [0.82, 0.89]; mean speed: 1.55 s^{-1}, 95% CI: [1.49, 1.62 s^{-1}]). They made a only few false alarms for the ignored uncompressed stream (false alarm rate: 0.03, 95% CI: [0.02, 0.04]; mean speed: 1.65 s^{-1}, 95% CI: [1.46, 1.84 s^{-1}]) and for the ignored compressed stream (false alarm rate: 0.03, 95% CI: [0.02, 0.04]; mean speed: 1.44 s^{-1}, 95% CI: [1.34, 1.55 s^{-1}]). Jointly, the number of hits and false alarms indicate that participants were attending to the cued speech stream. We found no significant difference in mean accuracy (b = 0.02, SE = 0.06, OR = 1.02, 95% CI [0.99, 1.14], p = .74) between the compressed and uncompressed streams.

NH participants responded with similar response speed to repeats in attend and ignored speech, no significant differences were observed (Figure 4 B left; b = 0.036, SE = 0.05, t(12268) = 0.74, p = 0.46). We found a significant main effect of

compression (b = 0.36, SE = 0.05, t(12260) = 7.36, p < .001), indicating that compression on speech streams led to a decreased response speed. However, this main effect was qualified by a significant interaction with attention (b = 0.69, SE = 0.1, t(12260) = 7.11, p < .001). A closer examination of the interaction via post hoc tests showed that the decrease in response speed on compressed speech was driven by ignoring (b = -0.7, SE = 0.1, t(12260) = -7.35, p < .001) not attending (b = -0.012, SE = 0.017, t(12260) = -0.7, p = 1). That is NH participants showed slower responses to false alarms in the ignore compressed stream.

Comparing the hit rate between the within attentional pairs of interest (attend uncompressed and ignore compressed vs. attend uncompressed and ignore uncompressed), we found no significant difference (b = -0.09, SE = 0.07, OR = 0.92, 95% CI [0.8, 1.01], p = .22)

We found a similar pattern comparing the response speed. No significant differences between attend uncompressed and ignore compressed vs. attend uncompressed and ignore uncompressed (b = -0.012, SE = 0.01, t(12252) = -1.2, p = .24).

We found that participants with hearing impairment (HI) were as well able to detect repeated sounds in both the uncompressed and compressed attended streams, with mean accuracies of 0.77 (95% double bootstrapped [CI]: [0.63, 0.86]) and 0.7 (95% double bootstrapped CI: [0.56, 0.81]), respectively (Figure 4 A right).

The difference in accuracy between the uncompressed and compressed attended streams was significant (mean difference: 0.06, 95 % double bootstrapped CI:[0.006, 0.101).HI participants also made very few false alarms in detecting repeated sounds in the ignored uncompressed and compressed streams, with mean accuracies of 0.14 (95% double bootstrapped CI: [0.02, 0.15]) and 0.06 (95% double bootstrapped CI: [0.02, 0.12]), respectively. The difference in false alarms between the compressed and uncompressed ignored streams was not significant (mean difference: 0.002, 95% double bootstrapped CI: [-0.04, 0.03]).

HI participants responded faster to repeated sounds in the uncompressed attended stream compared to the compressed attended stream, with mean response speed of 1.37 s−1 (95% double bootstrapped confidence interval [CI]:

[1.26, 1.5]) and 1.35 s−1 (95% double bootstrapped CI: [1.23, 1.48]), respectively (Figure 4 B right).

The difference in response speed between the uncompressed and compressed attended streams was significant (mean difference: 0.024 s−1, 95% double bootstrapped CI: [0.006, 0.043]). However, there was no significant difference in response speed between the uncompressed and compressed ignored streams, with mean response times of 1.37 s−1 (95% double bootstrapped CI: [0.97, 1.86]) and 1.37 s−1 (95% double bootstrapped CI: [1.05, 1.79]), respectively (mean difference: 0.18 s−1 , 95% double bootstrapped CI: [-0.46, 1.2]).

These results suggest that there is a significant difference in performance within the HI group between the uncompressed and compressed attended streams, with faster and more accurate responses for the uncompressed attended stream.

The results of the double iterative bootstrapping analysis for attentional pairs indicated that there were no significant differences between accuracy and speed in HI participants.

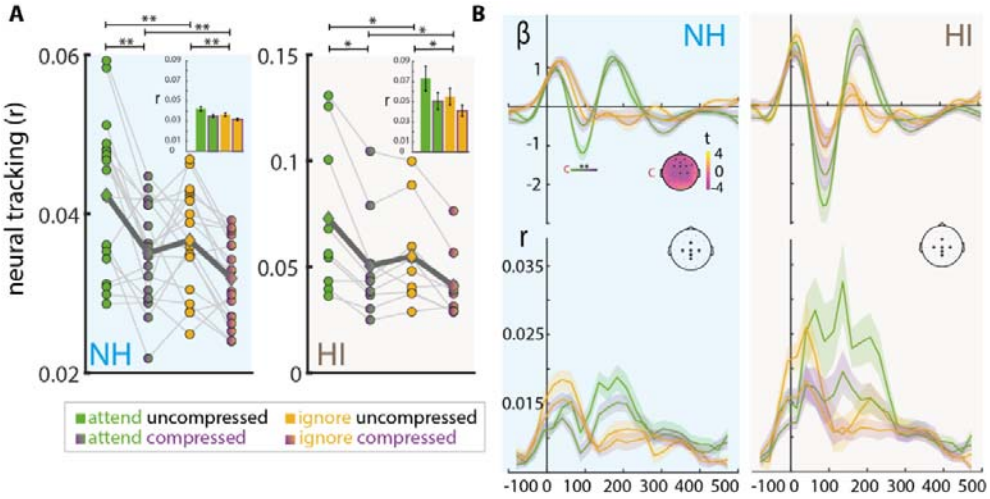

Figure 5. Neural tracking and temporal response functions (TRF). A Neural tracking (r) refers to the encoding accuracy (0-500 ms) obtained by multiplying estimated TRFs with the presented audio envelope. Spaghetti plot shows single-subject data (NH =24, HI = 9) averaged across channels of interest. Connection lines between dots indicate the same subject. Green dots indicate attend tracking, while orange dots indicate ignored tracking. Purple colour indicates compression. Insets show bar plots of neural tracking for NH and HI on the same scale. **B** Top: TRF β-weights are averaged across subjects (NH =blue, HI =brown) and channels of interest. Shaded areas depict the standard error for each time lag across subjects. Bottom: Unfolding neural tracking across time lags

(-100-500 ms). Solid lines show the averaged neural tracking (r) across subjects and channels of interest (topographic map). Shaded areas show the standard error for each time lag across subjects.

Compression decreases neural speech tracking in NH and HI participants

The strength of a speech stream's representation in the EEG is reflected by neural tracking (see methods for details). Analysis of the neural tracking (0-500 ms) revealed significant main effects of attention, which means that attended speech is stronger tracked than ignored speech ($b = 0.08$, $SE = 0.02$, $t(9185) = 3.9$, $p < .001$) and compression, which means that uncompressed speech is stronger tracked than compressed speech ($b = 0.13$, $SE = 0.02$, $t(9185) = 6.4$, $p < .001$; Figure 5 A). Attention and compression had no significant interaction ($b = -0.06$, $SE = 0.04$, $t(9185) = -1.36$, $p = .175$).

To assess the statistical significance of differences in TRFs between conditions, we used a cluster permutation test (Figure 5 B). We found a significant negative cluster (24–104 ms; cluster p-value < .001) which indicates a larger N1 amplitude for the attended signal, and a significant positive cluster (136-248 ms; cluster p-value < .001) which indicates a larger P2 amplitude for the attended signal between attended uncompressed and ignored uncompressed TRFs. When attend compressed and ignore compressed were compared, there was a significant negative (40-96 ms; cluster p-value =.005) and a significant positive (144-248 ms; cluster p-value = <.001) cluster. We found a significant negative cluster comparing attended uncompressed and attended compressed TRFs (56-112 ms; cluster p-value = .003) which indicates a larger N1 amplitude for the attended uncompressed signal. No significant clusters between ignore uncompressed and ignore compressed were observed.

To assess the statistical significance of differences in time-shifted neural tracking between conditions, we used a cluster permutation test (Figure 5 B). We found a significant positive cluster between attend uncompressed and ignore uncompressed (136-208 ms; cluster p-value = .001). Comparing attend compressed and ignore compressed revealed a significant negative (64-88 ms; cluster p-value = .04) and a significant positive cluster (136-160 ms; cluster p-value = .04). We observed no significant clusters between attend uncompressed and attend compressed, as well as between ignore unprocessed and ignore compressed.

Despite the small sample size of hearing-impaired participants, the neural tracking results are consistent (Figure 5 A). All participants showed increased neural tracking when they attended to signals compared to when they ignored them (mean: 0.014, 95% double bootstrapped CI: [0.038, 0.0243]). They also demonstrated significantly less neural tracking of compressed speech compared to uncompressed speech (mean: 0.018, 95% double bootstrapped CI: [0.011, 0.0274]). Furthermore, the difference in neural tracking between attending to uncompressed versus compressed speech was significant (mean: 0.022, 95% double bootstrapped CI: [0.0069, 0.0425]), as was the difference in neural tracking between ignoring uncompressed versus compressed speech (mean: 0.014, 95% double bootstrapped CI: [0.0044, 0.024]).

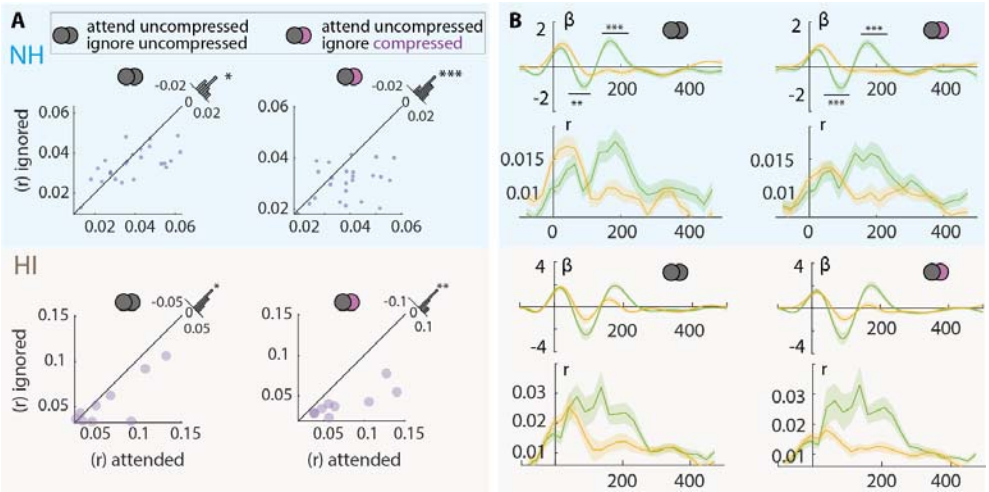

Figure 6. Neural tracking and TRF within attentional pairs for NH and HI participants. Overlapping double circle symbols indicate attentional pairs. A circle in the foreground indicates attending while a circle in the background indicates ignoring. Purple colour indicates compression. **A** Neural tracking (r) refers to the encoding accuracy (0-500 ms) based on estimated TRFs and envelopes. 45◦ plot shows single-subject data averaged across channels of interest for the four attentional pairs. **B** Top: TRF β-weights and time-shifted encoding accuracy are averaged across subjects and channels of interest for the four attentional pairs. Shaded areas depict the standard error for each time lag across subjects. Black bars indicate significant differences between attend and ignore TRF. Bottom: Unfolding neural tracking across time lags (-100-500 ms). Solid lines shows the averaged neural tracking (r) across subjects and channels of interest (topographic map). Shaded areas show the standard error for each time lag across subjects.

Increased neural separation due to decreased neural tracking of ignored stream

Analysis of the neural tracking (0-500 ms) within attentional pairs revealed (Figure 6 A) a significant effect of attention when both streams were uncompressed ($b = 0.11$, $SE = 0.046$, $t(9208) = 2.58$, $p = 0.01$). When only the ignored stream is compressed, we see significantly more neural tracking of the attended stream ($b = 0.2$, $SE = 0.04$, $t(9208) = 4.9$, $p < .001$). There was no significant difference between attend compressed and ignore uncompressed ($b = -0.03$, $SE = 0.04$, $t(9208) = -0.83$, $p = .406$) and when both streams were compressed ($b = 0.05$, $SE = 0.04$, $t(9208) = 1.1$, $p = .263$).

To assess the statistical significance of differences in TRFs within pairs, we used a cluster permutation test (Figure 6 B). We found one negative and one positive cluster (PC, NC) for each attentional pair: attend uncompressed & ignore uncompressed (NC: 40-104 ms, cluster p-value = .002; PC: 136-232 ms, cluster p-value < .001), attend uncompressed & ignore compressed (NC: 40-112 ms, cluster p-value = < .001; PC: 144-248 ms, cluster p-value < .001), attend compressed & ignore uncompressed (NC: 32-88 ms, cluster p-value = .03; PC: 128-240 ms, cluster p-value < .001) and attend compressed & ignore compressed (NC: 40-104 ms, cluster p-value = .002; PC: 152-248 ms, cluster p-value < .001).

We conducted an analysis of neural tracking (0-500 ms) within attentional pairs (attend vs. ignore; Figure 6 A) and found no significant difference when both streams were uncompressed (mean: 0.015, 95% double bootstrapped CI: [-0.0037, 0.0475]). However, we did observe a significant difference in the attentional pair when only the ignored stream was compressed (mean: 0.035, 95% double bootstrapped CI: [0.0095, 0.0750]).

Upon visual inspection of the temporal response functions (TRFs) and time-shifted neural tracking, we found that they were consistent with the neural tracking results (Figure 6 B). Overall, in attentional pairs, the attended TRFs showed the typical P1-N2-P2 succession. Additionally, the P1 component of both the attended and ignored TRFs had similar amplitudes across all attentional pairs. However, the difference between the attended and ignored streams varied between attentional pairs for the N1 time window (approximately 80-120 ms). The largest separation occurred in the attend uncompressed and ignore compressed pair, followed by the attend and ignore uncompressed and attend and ignore compressed pairs. These findings were consistent with the time-shifted neural

tracking results, which indicated similar neural separation relations in attentional pairs.

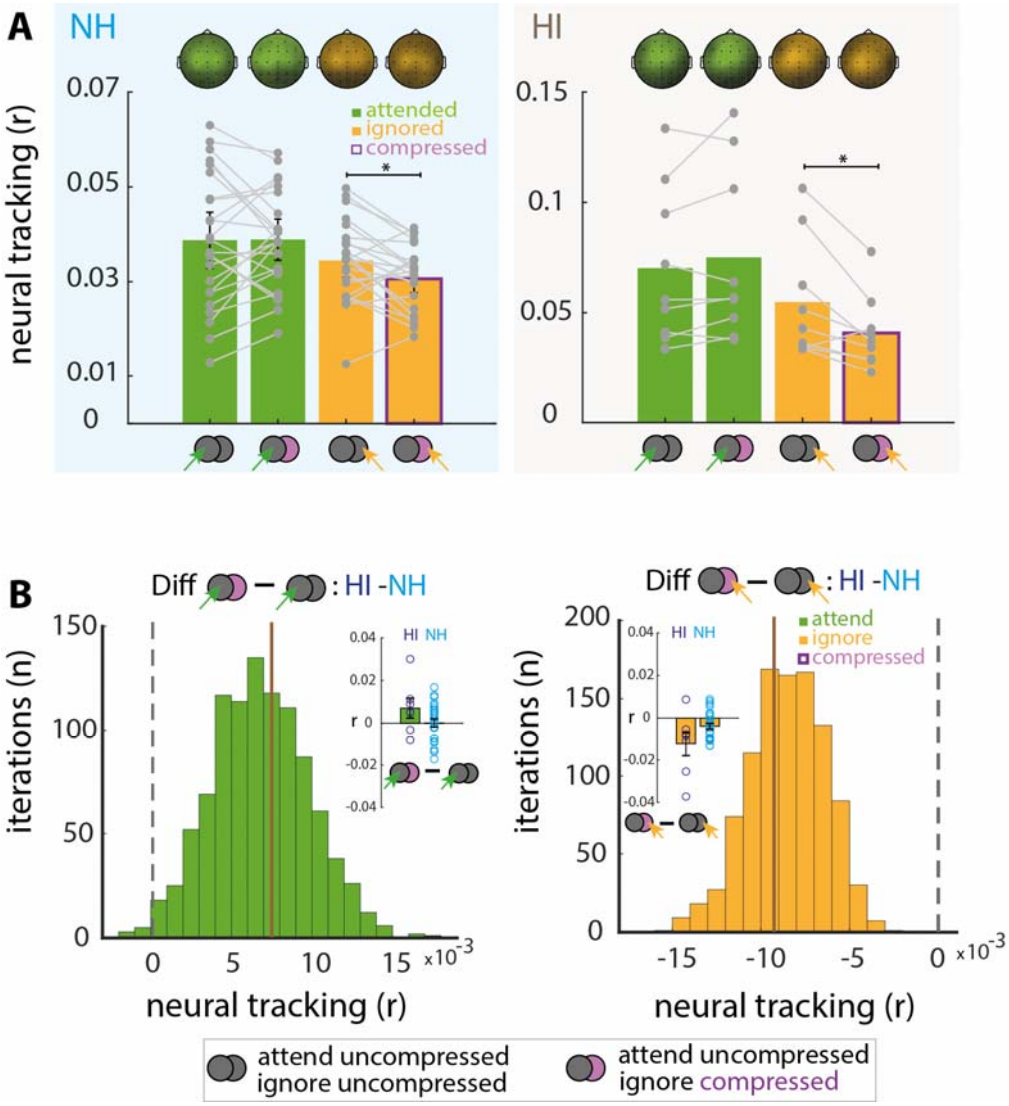

Figure 7. Comparison between attended and ignored neural tracking arising from different simultaneously presented attentional pairs for NH and HI participants.). **A** show the comparison between attended and ignored streams from attend and ignore uncompressed pairs vs. attend uncompressed and ignore compressed pairs. Overlapping double circle symbols indicate attentional pairs. Neural tracking (r) refers to the encoding accuracy (0-500 ms) based on estimated TRFs and envelopes. The purple colour indicates compression. The bar plot shows the participant's group mean (green = attend, orange = ignore), and single subject data are depicted as grey circles. Connection lines indicate the same subject. Error bars show a 95% CI. Topographic maps (green = attend, orange = ignore) depict average neural tracking (0-500 ms. **B** Comparison of the neural tracking differences between the attended streams (left) and ignored streams (right) between hearing-impaired (HI) and normal hearing (NH) participants for selected pairs. Distributions were obtained by randomly selecting seven

participants from the NH group and comparing their neural tracking to that of the HI group. This process was repeated 1000 times to obtain an average difference between the two groups. The solid vertical lines (brown) indicate the average difference across iterations, while the dashed line indicates zero, which would indicate no difference between HI and NH. Inset shows differences in neural tracking between the attended and ignored streams for the attentional pair comparison, respectively. Bar plot shows participant's mean and single-subject data are depicted as circle. Dark blue circle indicates HI and light blue circle NH participants. Error bars show the standard error (SEM).

Based on our second hypothesis that compression on the ignored stream increases the neural separation between the attended and ignored streams, we took a closer look on the attentional differences between attended uncompressed & ignore uncompressed vs. attended uncompressed & ignore compressed (Figure 7 A). In NH participants, there were no statistically significant differences between the attended uncompressed streams from both pairs (b = -0.003, SE = 0.04, t(9208) = -0.08, p = 0.9). We found a significant difference between the ignored uncompressed and ignored compressed stream (b = 0.09, SE = 0.04, t(9208) = 2.3, p = 0.02) which indicates less neural tracking for the compressed ignored stream.

To investigate whether the neural separation is larger in the hearing-impaired when the ignored stream is compressed, we compared the attentional pairs in which both streams are unprocessed to the pair in which only the ignored stream is compressed and the attended stream is uncompressed also in hearing-impaired participants. We compared the attended (mean: -0.007, 95% double bootstrapped CI: [-0.0244, 0.0068]) and ignored (mean: 0.0123, 95% double bootstrapped CI: [0.0024, 0.0252]) streams between the "attend uncompressed and ignore uncompressed" pair and the "attend uncompressed and ignore compressed" pair. The results showed no significant difference between the two pairs. However, visual inspection of the individual participants' data revealed that most (6 out of 9) participants showed increased neural tracking for attend, and most (8 out of 9) showed decreased neural tracking for ignore for the" attend uncompressed ignore compressed" attentional pair (Figure 7 A).

We compared the differences in neural tracking between the attended and ignored speech streams for two attentional pairs:" attend uncompressed and ignore uncompressed" and" attend uncompressed and ignore compressed", between a group of 24 normal hearing control participants and a group of 9 hearing-impaired participants (Figure 7 B). To obtain the differences in neural tracking between the

two groups, we randomly selected 9 participants from the normal hearing group and compared their neural tracking differences to that of the hearing-impaired group. This process was repeated a thousand times to obtain a distribution of the iterative differences between the two groups.

Differences in attended streams between the groups were mostly larger for the HI participants (mean: 0.0069, 95% CI: [0.067, 0.070]). However, the differences in ignored stream between the groups were consistently larger in the hearing-impaired listeners across all iterations (mean: -0.0086, 95% CI: [-0.0084, -0.0087]).

Control analysis: Front–back location assignment does not confound neural and behavioural results

We considered the possibility that the front–back location assignment could have an indirect effect on our behavioural and neural measures. Between trials (and for some sustained trials), participants had to switch their attention between the front and back loudspeakers. We had randomized and balanced conditions across the two locations of the streams. Nevertheless, location as a factor was included in the statistical analysis to control for potential confounds.

We analysed the effects of location (front–back), attention, and compression on both behavioural performance and response time in normal hearing participants. Our results showed a significant main effect of location on behavioural performance ($b = 0.26$, $SE = 0.06$, $OR = 1.3$, 95% CI [1.16, 1.45], $p < .001$), indicating that participants detected more repeats in the front loudspeaker.

Importantly, however, there were no significant interactions between location and attention ($b = -0.01$, $SE = 0.11$,$OR = 0.99$, 95% CI [0.79, 1.24], $p = 0.9$), between location and compression ($b = -0.14$, $SE = 0.11$, $OR = 0.87$, 95% CI [0.7, 1.01], $p = 0.2$), or between location, compression, and attention ($b = -0.22$, $SE = 0.23$, $OR = 0.8$, 95% CI [0.51, 1.26], $p = 0.33$).

Regarding response speed, we observed no significant main effect of location ($b = 0.02$, $SE = 0.05$, $t = 0.44$, $p = 0.66$) and no significant interactions between location and attention ($b = -0.08$, $SE = 0.1$, $t = -0.8$, $p = 0.43$), between location and compression ($b = -0.01$, $SE = 0.1$, $t = -0.1$, $p = 0.92$), and between location, compression, and attention ($b = -0.02$, $SE = 0.19$, $t = -0.09$, $p = 0.93$).

Our neural analysis showed no significant main effect of location (b = -0.02, SE = 0.02, t = -1.04, p =0.3), and we found no significant interactions between location and attention (b = -0.03, SE = 0.04, t = -0.8, p = 0.43), between location and compression (b = -0.06, SE = 0.04, t = -1.34, p = 0.175), or between location, compression, and attention (b = -0.03, SE = 0.08, t = -0.312, p = 0.76). Therefore, our results suggest that the front-back location assignment did not confound the neural and behavioural measures in normal hearing participants.

Hearing-impaired participants correctly detected repeats on average with a proportion of 0.76 (95% CI [0.64, 0.88]) in the front loudspeaker, while they correctly detected a proportion of 0.71 (95% CI [0.63, 0.79]) in the back loudspeaker. They responded with similar response speed to the front (mean: 1.37 s^{-1}, 95% CI [1.24, 1.49]) and back loudspeaker (mean: 1.36 s^{-1}, 95% CI [1.23, 1.5]).

In our neural analysis, hearing-impaired participants show a mean neural tracking of 0.06 (95% CI [0.03, 0.09]) for attended and 0.046 (95% CI [0.03, 0.06]) for ignored speech presented over the frontal loudspeaker. In contrast, they show a mean neural tracking of 0.052 (95% CI [0.03, 0.07]) for attended and 0.04 (95% CI [0.03, 0.05]) for ignored speech presented over the back loudspeaker.

Control analysis: Auditory peripheral modelling of compressed and uncompressed speech

To avoid a potential peripheral, confound on our neural data, we modelled the peripheral response to our stimulus material. Therefore, we employed a computational model of the human auditory periphery developed by Verhulst et al. (2018).

We used a mixed model to analyse the AN output (Figure 8 A), with hearing status (NH vs. HI), signal manipulation (uncompressed vs. compressed), and frequency (500, 1000, 2000, and 4000 Hz) as fixed effects, and speech snippet as a random effect. Our analysis revealed a significant main effect of hearing status ($b = 0.053$, $SE = 0.02$, $t = 2.4$, $p = 0.016$), indicating higher log-transformed spike rates in the NH group compared to the HI group. We also observed a significant main effect of frequency (ref:1000 Hz; $b = -1.3$ to 0.9, $SE = 0.03$, $t = -42$ to 29, $p < .001$ for all), indicating higher log-transformed spike rates for higher frequencies. There was no significant main effect on signal manipulation ($b = 0.004$, $SE = 0.02$, $t = .2$, $p = 0.9$) In addition, there was a significant interaction between frequency and signal manipulation (overall, $p = 0.003$). No other interactions were significant (all $p > 0.05$). Overall, our results indicate that both hearing status and frequency have a significant impact on AN output.

Upon visual inspection the EFR (Figure 8 B), if at all, the compressed speech snippets appeared to lead to a higher amplitude in both simulations for normal hearing and hearing-impaired.

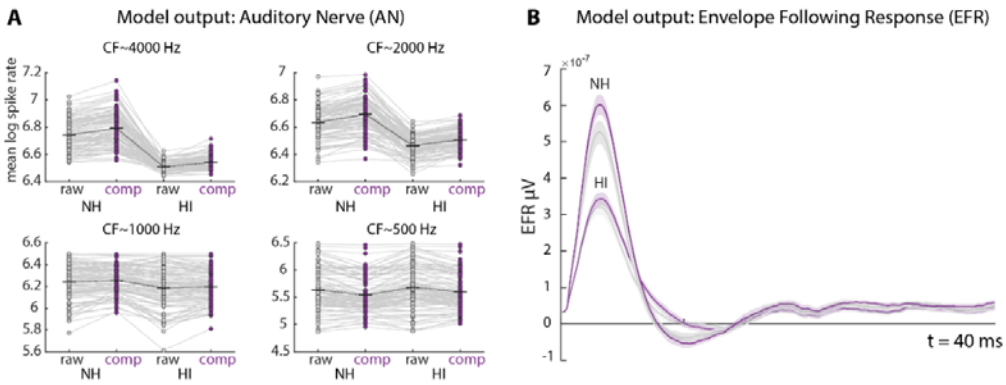

Figure 8. Simulated model output: AN and EFR. Panel **A** displays AN output for four center frequencies (500, 1000, 2000, and 4000 Hz), separated by normal hearing (NH) and hearing-impaired (HI) conditions and uncompressed (raw) and

compressed (comp) speech snippets. Dots indicate different speech snippets. Connection lines indicate same snippet. Panel B shows the simulated EFR for NH and HI conditions, separate for compressed and uncompressed speech snippets. Shaded area shows SEM of different snippets, while solid line shows the mean across snippets. The colour purple indicates compression.

Discussion

In the present study, we aimed to investigate the effects of amplitude compression and its interactions with a listener's selective attention goals on neural separation and listening behaviour. Studying normal and hearing-impaired participants using a psychophysically augmented continuous speech paradigm, our hypothesis was that compression decreases neural tracking. Furthermore, we expected that compression on ignored talkers could improve neural and behavioural markers of attentional separation.

Amplitude compression on speech impairs listening performance

Normal hearing- and hearing-impaired participants showed decreased behavioural responses when primarily the attended streams were compressed. The findings are consistent with prior research indicating that fast-acting compression leads to reduced speech intelligibility (Drullman et al., 1994; Stone & Moore, 2004).

Two decades ago, Stone & Moore (2004, 2007) first explored compression affecting decreased performance. They introduced the term "across-source modulation correlation" Compression leads signals with peaks to decrease in gain for the entire mixture, causing previously independent signals to acquire a common modulation component, reducing their independence, and increasing the likelihood of perceptual fusion. Important for the present study's rationale, comodulation arising from compressed speech signals may cause perceptual fusion of attended and ignored speech, disrupting auditory grouping. If multiple speech signals with similar comodulation are presented simultaneously, they can render separation challenging (Bregman, 1994; Bregman et al., 1985; Hall III & Grose, 1990). Notably, such comodulation issues would only arise when compressing the mixture of attended and ignored signals. Our study used separate amplitude modulation on each stream, ensuring that our results are not influenced by comodulation of both streams (Stone & Moore, 2004).

Unlike comodulation, modulation reduction through compression is crucial in the present design. Our loudness matching pipeline's dynamic range compressor adjusted gain based on intense signal components, typically corresponding to envelope peaks. Fast amplitude compression, employed in our pipeline, focuses on these peaks, reducing their gain. The pipeline enhances low-intensity signals, resulting in smaller amplitude modulation depth in compressed speech, distorting

envelope fidelity (Stone & Moore, 1992). The non-instantaneous compressor operation can cause overshoots and undershoots, contributing to envelope distortion (Shetty, 2016; Verschuure et al., 1996).

When delving deeper into the repercussions of fast amplitude compression on speech signals, an intriguing facet emerges, namely the differential impact on high-intensity vowel components and low-intensity consonant elements. High-intensity parts of a speech signal are typically associated with vowels, while low intensity parts are associated with consonants, loudness matched compressed speech will attenuate vowels while enhancing consonants. This results in a distortion of the speech signal and a decrease in the ratio between vowels and consonants. Multiple studies have shown that fast amplitude compression can reduce amplitude modulation depth and intensity contrast (Moore et al., 2003; Plomp, 1988). This is crucial for speech recognition as it primarily relies on the temporal cues of speech (Peelle et al., 2013; Shannon et al., 1995; Shetty, 2016; Stone & Moore, 2004). Furthermore, both speech streams are subject to reduced amplitude modulation, even though they are not comodulated. This means that they share a similar low amplitude modulation ratio, which can make it more difficult to separate the two streams (Grimault et al., 2002).

Amplitude compression decreases neural tracking of speech

To our knowledge, we have here presented the first study to explore the impact of amplitude compression on neural speech tracking using EEG recordings in both normal hearing and hearing-impaired individuals. Our findings revealed a significant effect of amplitude compression on neural tracking in normal hearing- and hearing-impaired participants.

Neural speech tracking relies on the temporal envelope of speech, as has been previously shown in various studies (Ding & Simon, 2012; Etard & Reichenbach, 2019; Kadir et al., 2019; Kerlin et al., 2010; Mesgarani & Chang, 2012; Obleser & Kayser, 2019; Rosen, 1992; Zion Golumbic et al., 2013). Therefore, it was expected that dynamic range compression, a form of signal processing that directly affects the temporal envelope of speech, might impair neural speech tracking. As described in more detail above, the fidelity of the temporal envelope is impaired (vowel to consonant ratio) due to reduction in amplitude modulation depth and overshoot and undershoots in amplitude compressed speech (Stone & Moore, 2007, 2007; Verschuure et al., 1996).

In the context of selective attention, our results showed a main effect of attention on neural tracking, with larger tracking of the attended speech compared to the ignored speech. This is in line with several previous studies that have shown enhanced neural responses to attended speech compared to ignored speech (e.g., Mesgarani & Chang, 2012; Zion Golumbic et al., 2013). We did not observe a significant interaction between compression and attention on neural tracking, suggesting that compression did not modulate the effect of selective attention on neural tracking in the first place.

Given the quasi-factorial nature of our experimental design, where attended and ignored speech streams are presented simultaneously, we focused also on attentional pairs. Our hypothesis was that compressing only the ignored stream would enhance neural separation between attended and ignored streams. We anticipated decreased neural tracking for the compressed ignored stream and increased tracking for the attended stream, even when both were unprocessed. We found a significant difference in neural tracking between compressed and uncompressed ignored streams in both groups but no significant difference in tracking for uncompressed attended streams among normal hearing participants. However, there was a tendency that hearing-impaired participants indicate also larger tracking of the uncompressed attended streams.

Hearing-impaired participants showed larger differential neural tracking responses compared to normal hearing participants

Comparing hearing-impaired and normal hearing participants, we observed larger differential tracking in hearing-impaired individuals between the attended and ignored streams. Normal hearing participants performed well, and the compression manipulation on the ignored stream might not have triggered the need for distractor suppression or target enhancement. In contrast, hearing-impaired participants tended to perform worse overall, potentially benefiting more from a compressed ignored talker. The comparison between normal hearing (NH) and hearing-impaired (HI) participants in the compressed versus uncompressed ignored streams consistently showed weaker tracking in HI participants, suggesting additional suppression of the compressed stream. This could facilitate the processing of the attended stream, leading to increased neural tracking. However, to cleanly distinguish between target enhancement and distractor suppression, an additional baseline would be beneficial (Orf et al., 2023; Wöstmann et al., 2022).

For normal hearing participants, these findings endorse the idea that compression diminishes neural speech processing, leading to decreased neural tracking. The primary factor driving this effect is likely the distortion of envelope fidelity, as previously discussed. However, for hearing-impaired participants, there may be more to uncover. Future studies should explore whether hearing-impaired individuals might also experience benefits from more pronounced compression applied to ignored streams.

Limitations

First, an obvious limitation of our lies in incorporating only N=9 hearing-impaired participants. This small sample of hearing-impaired individuals obviously restricts generalizability, and variability in hearing profiles and responses among hearing-impaired individuals could affect the overall trends observed. Also, the small sample size may limit the detection of subtle effects or interactions, highlighting the need for future research with larger and more diverse samples for a comprehensive understanding of the impact of amplitude compression on attentional neural speech tracking in this population. However, it is important to note that the hearing loss was similar in terms of slope and PTA among hearing impaired participants. Also, the relative imbalance to the solidly sized N=24 normal-hearing sample was taken care of through iterative subsampling (see Fig. 7). Not least, a previous study (Verschueren et al., 2021) reported that neural speech tracking is robust to stimulus intensity, and the attention and compression effects were consistent despite the small sample size.

Second, using a computational model for auditory peripheral modelling, specifically focusing on the auditory nerve and the envelope following response, has its limitations compared to real measurements. Computational models inherently simplify the intricate biological processes of the auditory system. While such models aim to replicate physiological responses, they may not fully capture the complexity and variability of real neural responses. Limitations include assumptions made in modelling, potential oversimplifications of neural processing, and uncertainties in translating model outputs to real-world neural responses. Moreover, individual differences in the auditory system among participants may not be fully accounted for in a computational model. For a more comprehensive understanding, incorporating real measurements of the auditory periphery in future studies would enhance the validity and applicability of findings to actual neural responses in individuals.

Conclusions

We here explored whether amplitude compression aids or hinders attentional neural speech tracking, for normal hearing as well as hearing-impaired participants. For normal hearing participants, applying amplitude compression to both streams hampers neural speech tracking, and no benefit from compression applied solely to the ignored stream is evident. While these findings generally extend to hearing-impaired participants, they exhibit a curious benefit in attentional separation in terms of neural speech tracking when the ignored speech stream is amplitude-compressed. Using modern hearing aid algorithms that allow varying compression ratios for different spatial sources or investigating multiple distractors that become comodulated and fuse as one distracting source, could provide valuable insights into the psychoacoustic and neurophysiological effects of amplitude compression and its potential benefits.

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Declaration of interests

Ronny Hannemann is an employee of WS Audiology. The authors declare no competing interests.

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