The effect of stimulus choice on an EEG-based objective measure of speech intelligibility

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ABSTRACT

Objectives Recently an objective measure of speech intelligibility, based on brain responses derived from the electroencephalogram (EEG), has been developed using isolated Matrix sentences as a stimulus. We investigated whether this objective measure of speech intelligibility can also be used with natural speech as a stimulus, as this would be beneficial for clinical applications.

Design We recorded the EEG in 19 normal-hearing participants while they listened to two types of stimuli: Matrix sentences and a natural story. Each stimulus was presented at different levels of speech intelligibility by adding speech weighted noise. Speech intelligibility was assessed in two ways for both stimuli: (1) behaviorally and (2) objectively by reconstructing the speech envelope from the EEG using a linear decoder and correlating it with the acoustic envelope. We also calculated temporal response functions (TRFs) to investigate the temporal characteristics of the brain responses in the EEG channels covering different brain areas.

Results For both stimulus types the correlation between the speech envelope and the reconstructed envelope increased with increasing speech intelligibility. In addition, correlations were higher for the natural story than for the Matrix sentences. Similar to the linear decoder analysis, TRF amplitudes increased with increasing speech intelligibility for both stimuli. Remarkable is that although speech intelligibility remained unchanged, neural speech processing was affected by the addition of a small amount of noise: TRF amplitudes across the entire scalp decreased between 0 to 150 ms, while amplitudes between 150 to 200 ms increased. TRF latency changes in function of speech intelligibility appeared to be stimulus specific: The latency of the prominent negative peak in the early responses (50-300 ms) increased with increasing speech intelligibility for the Matrix sentences, but remained unchanged for the natural story.

Conclusions These results show (1) the feasibility of natural speech as a stimulus for the objective measure of speech intelligibility, (2) that neural tracking of speech is enhanced using a natural story compared to Matrix sentences and (3) that noise and the stimulus type can change the temporal characteristics of the brain responses. These results might reflect the integration of incoming acoustic features and top-down information, suggesting that the choice of the stimulus has to be considered based on the intended purpose of the measurement.

1 INTRODUCTION

In current clinical practice speech intelligibility is measured behaviorally by asking the listeners to recall the words or sentences they heard. By doing so, not only the function of the auditory periphery is measured, but also working memory, language knowledge, cognition and speech production. When measuring speech intelligibility to evaluate the function of a hearing aid, it can be desirable to evaluate the auditory periphery without these extra factors. In addition, the required active participation of the patient can make these measurements challenging or even impossible because of poor attention or motivation, especially in small children.

To overcome these challenges an objective measure of speech intelligibility, where no input from the patient is required, would be of great benefit. Previous studies have shown that the slowly varying speech envelope is essential for speech intelligibility (Shannon et al., 1995), and that it can be reconstructed from brain responses using electroencephalography (EEG) or magnetoencephalography (Luo and Poeppel, 2007; Aiken and Picton, 2008; Ding and Simon, 2011). Correlating the reconstructed envelope from the brain response with the real acoustic envelope, results in a measure of neural envelope tracking, which is related to speech intelligibility (Luo and Poeppel, 2007; Ding et al., 2014; Millman et al., 2015; Molinaro and Lizarazu, 2017; Vanthornhout et al., 2018; Lotzov and Parra, 2019; Lesenfants et al., 2019).

Vanthornhout et al. (2018) and Lesenfants et al. (2019) demonstrated the application of this measure of neural envelope tracking in an objective measure of speech intelligibility using isolated Matrix sentences as a stimulus. In their studies the same Matrix sentences were used during a standardized behavioral recall experiment and an EEG measurement, enabling direct comparison of speech intelligibility to envelope tracking. However, for the purpose of clinical applications, the use of isolated sentences may be sub-optimal. Sentences do not reflect everyday communication where syllable, word and sentence rate are less controlled and more semantic top-down processing is involved. Therefore, an objective measure of speech intelligibility based on fully natural speech would (1) overcome the patient-related challenges linked to attention and motivation (2) and allow intelligibility measurements of any speech fragment, which is impossible today using behavioral measurements but may relate better to everyday communication.

In this study we investigated whether the objective measure of speech intelligibility by Vanthornhout et al. (2018) using Matrix sentences can also be conducted with natural running speech, such as a narrated story. We hypothesized that a difference in neural envelope tracking between the two stimuli may be related to the interactive process of speech processing. Speech intelligibility namely relies on the active integration of two incoming information streams (Hickok and Poeppel, 2007; Anderson et al., 2018): (1) the bottom-up stream that processes the acoustic features through the auditory pathway until the auditory cortex and (2) the top-down stream originating in different brain regions. We hypothesized that if neural envelope tracking is mainly a feed-forward acoustic process, results for Matrix sentences will be enhanced compared to the story because of the rigid syllable, word and sentence rate reflected in the speech envelope of the Matrix sentences. If, on the other hand, neural envelope tracking captures the interaction between the incoming acoustic speech stream and top-down information, results for the story will be enhanced because of, e.g., increased semantic processing (Di Liberto et al., 2018; Broderick et al., 2018) and attention (Kerlin et al., 2010; Ding and Simon, 2012; Mesgarani and Chang, 2012; Vanthornhout et al., 2019).

2 MATERIAL AND METHODS

2.1 Participants

Nineteen participants aged between 18 and 28 years (3 men and 16 women) took part in the experiment after providing informed consent. Participants had Flemish as their mother tongue and were all normal-hearing, confirmed with pure tone audiometry (thresholds $\leq$ 25 dB HL at all octave frequencies from 125 Hz to 8 kHz). The study was approved by the Medical Ethics Committee UZ Leuven / Research (KU Leuven) with reference S57102. All participants were unpaid volunteers.

2.2 Auditory stimuli

During the experiment participants listened to three different stimuli: (1) isolated Matrix sentences, (2) a natural story and (3) another story used to train the linear decoder on.

2.2.1 Matrix sentences

Flemish Matrix sentences contain 5 words spoken by a female speaker and have a fixed syntactic structure of ‘proper name-verb-numeral-adjective-object’, for example, ‘Sofie sees ten blue socks’ with a speech rate of 4.1 syllables/second, 2.5 words/second and 0.5 sentences/second. Each category of words has 10 alternatives and each sentence consists of a random combination of these alternatives which induces a rigid and artificial speech rate and reduces semantic context to a bare minimum. These sentences are gathered into standardized lists of 20 sentences. Speech was fixed at a level of 60 dBA and the noise level varied across trials. We used speech weighted noise (SWN) which has the long-term-average spectrum of the stimulus and therefore results in optimal energetic masking. Matrix sentences are a validated speech material to measure speech intelligibility which allows us to directly compare EEG results with speech intelligibility, similar to Vanthornhout et al. (2018) and Lesenfants et al. (2019). However, Matrix sentences have a rigid speech rate and lack semantic information, resulting in an artificial speech stimulus not representative for everyday communication.

2.2.2 Natural story

The natural story we used is ’De Wilde Zwanen’, written by Hans Christian Andersen and narrated in Flemish by Katrien Devos (female speaker) with a speech rate of approximately 3.5 syllables/second, 2.5 words/second and 0.2 sentences/second. Speech was fixed at a level of 60 dBA and the noise level of the SWN varied across trials. The main differences between the Matrix sentences (2.2.1) and fully natural speech such as this narrated story are:

1. *Prosody*: Matrix sentences are part of a standardized speech material where every word is spoken at the same intensity, while the story is naturally spoken with intensity variations as a consequence.
2. *Speech rate*: Matrix sentences have a rigid syllable, word and sentence rate, while the story has a naturally varying speech rate because of different word and sentence lengths.
3. *Semantic context*: Matrix sentences are a random combination of words, minimizing the use of semantic context. The story, on the other hand, is coherent speech where the use of top-down processing is triggered, e.g., knowledge about time, space and characters.
4. *Lexical prediction*: The permutations of the words are different in each Matrix sentence, but the words themselves become more familiar to the participants during the experiment, in contrast to the story.

2.2.3 Decoder story

A children's story, 'Milan', written and narrated in Flemish by Stijn Vranken (male speaker), was presented to the participants with a speech rate of 3.7 syllables/second, 2.6 words/second and 0.3 sentences/second. This story is 14 minutes long and was presented at a level of 60 dBA without noise. The purpose of this story was to have an independent continuous stimulus without background noise to train a linear decoder on (Vanthornhout et al., 2018) to reconstruct the speech envelope from the EEG.

2.3 Behavioral experiment

Speech intelligibility was measured behaviorally in order to compare envelope tracking results in terms of speech intelligibility. We need to measure speech intelligibility for both stimuli separately because they differ in content and acoustic parameters (speaker, speech rate, intonation). Adding a similar level of background noise will therefore not result in a similar level of speech intelligibility (Decruy et al., 2018).

Before the EEG experiment we conducted a standardized Matrix test. This standardized test starts with 2 training lists followed by 3 testing lists of 20 sentences at different Signal-to-Noise Ratios (SNR): -9.5; -6.5 and -3.5 dB SNR. Participants had to recall the sentence they heard. By counting the correctly recalled words, a percentage correct per presented SNR was calculated. Next, a psychometric function was fitted on the data points, similar to what is done in clinical practice. To measure speech intelligibility for the story, we cannot ask the participants to recall every word, instead we used a rating method during the EEG experiment. Participants were asked to rate their speech intelligibility with the following question: 'Which percentage of the words did you understand?' at the presented SNRs (-12.5; -9.5; -6.5; -3.5; -0.5 and 2.5 dB SNR). In addition to the recall procedure for the Matrix sentences before the EEG experiment, we also asked 9 of the 19 participants to rate their speech intelligibility for the Matrix sentences during the EEG, similar to the story.

2.4 EEG experiment

Ten participants started the EEG experiment by listening to Matrix sentences followed by the natural story. The remaining 9 participants did this in the reversed order. The decoder story was presented in between. The natural story was cut in 7 equal parts of approximately 4 minutes long, which we presented in chronological order. The first part was always presented in silence to optimize comprehension of the storyline. The following 6 parts were presented at 6 different SNRs in random order: -12.5; -9.5; -6.5; -3.5; -0.5 and 2.5 dB SNR. The Matrix sentences were concatenated into 7 lists of 40 sentences with a silent gap between the sentences randomly varying between 0.8 and 1.2 seconds. Each 2-minute trial, containing 40 sentences at a particular SNR, was presented twice to analyze test-retest reliability. The SNRs were the same SNRs as used for the story, also in random order. To maximize attention and keep the participants motivated, questions were asked about each SNR trial, for example, 'What happened after sunset?' (story) or 'Which colors of boats were mentioned?' (Matrix sentences). The answers were not used for further analysis. After the question, the participants were asked to rate their speech intelligibility with the following question: 'Which percentage of the words did you understand?' as mentioned in section 2.3.

2.5 Signal processing

In this study we measured neural envelope tracking and linked this to speech intelligibility and stimulus type (natural story versus isolated Matrix sentences). Neural envelope tracking was calculated in two ways: We correlated the acoustic speech envelope (2.5.1) with the speech envelope reconstructed from the EEG respons (2.5.2) with the help of a linear decoder. Secondly, we calculated temporal response functions (TRFs) to investigate the temporal characteristics of the brain responses in the EEG channels covering the scalp (2.5.3).

2.5.1 Acoustic envelope

The acoustic speech envelope was extracted from the stimulus according to Biesmans et al. (2017), using a gammatone filterbank followed by a power law. We used a filterbank containing 28 channels spaced by 1 equivalent rectangular bandwidth with center frequencies from 50 Hz until 5000 Hz. The absolute value of each sample in each channel was raised to the power of 0.6. All 28 channel envelopes were averaged which resulted in one single envelope. As a next step, the acoustic speech envelope was band-pass filtered, similar to the EEG signal, in the delta (0.5-4 Hz) or theta (4-8 Hz) frequency band with a Chebyshev filter with 80 dB attenuation at 10% outside the passband. Only these low frequencies were further processed, because they contain the information of interest of the slowly varying speech envelope.

2.5.2 Envelope reconstruction

As a first step the EEG data was downsampled from 8192 Hz to 256 Hz to reduce processing time and referenced to an average of the electrodes. Next, EEG artefact rejection was done using a multi-channel Wiener filter (MWF) (Somers et al., 2018). the MWF was calculated on the long decoder story without noise and applied on the shorter Matrix and coherent story SNR trials. After artefact rejection, the signal was bandpass filtered, similar to the acoustic speech envelope and the sample rate was further decreased from 256 Hz to 128 Hz. A schematic overview is shown in Figure 1.

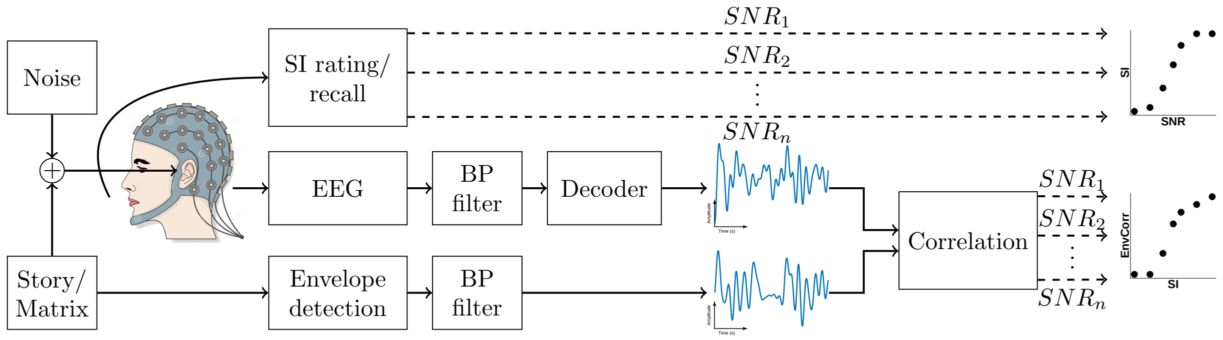


Figure 1. Overview of the experimental setup using the linear decoder analysis. We presented the Matrix sentences and a story at different Signal-to-Noise Ratio's (SNR). Participants listened to the speech while their EEG was measured. To obtain a measure of neural envelope tracking we correlated the reconstructed envelope with the acoustic envelope after band-pass filtering (BP filter). We compared the envelope tracking results with the behavioral speech intelligibility (SI) scores.

To enable reconstruction of the speech envelope from the neural data as a measure of neural envelope tracking, a linear decoder was created using the mTRF toolbox (Lalor et al., 2006, 2009). As speech elicits neural responses with some delay, the decoder not only attributes weights to each EEG channel (spatial filter), but it also takes the shifted neural responses of each channel into account (temporal filter), resulting in a matrix R containing the shifted neural responses of each channel. If g is the linear decoder and R the shifted neural data, the reconstruction of the speech envelope $\hat{s}(t)$ was obtained by $\hat{s}(t) = \sum_n \sum_\tau g(n,\tau)R(t+\tau,n)$ with t the time index, n ranging over the recording electrodes and τ ranging over the integration window, i.e., the number of post-stimulus samples used to reconstruct the envelope. The decoder was calculated by solving $g = (RR^T)^{-1}(Rs^T)$ with s the speech envelope and applying ridge regression to prevent overfitting. We used an integration window of 250 ms post-stimulus resulting in the decoder matrix g of 64 (EEG channels) x 33 (time delays within the integration window). The decoder was created using the Milan story (14 minutes) without any noise.

As a last step the envelope was reconstructed by applying the decoder to both test stimuli, the Matrix sentences and the natural story, at various noise levels. Each SNR trial consisted of 2 presentations of 80 seconds of speech (silences excluded). To measure how similar this reconstructed envelope was to the acoustic envelope as a measure for neural envelope tracking, we calculated the bootstrapped Spearman correlation using Monte Carlo sampling after removing the silences in the stimulus and the corresponding part in the EEG. Removing the silences is necessary as the Matrix sentences contain quasi-regular silent gaps between the sentences which would be a confound.

The significance level of the correlation was calculated by correlating random permutations of the real and reconstructed envelope 1000 times and taking percentile 2.5 and 97.5 to obtain a 95% confidence interval.

2.5.3 Temporal response function estimation

The analysis above integrates all neural activity over channels and time lags and requires a decoder trained on a separate story. To have a closer look at the spatiotemporal profile of the neural responses and remove the assumption that neural processing is similar for the decoder story and the test stimuli in different noise conditions, we calculated TRFs. A TRF is a linear filter that describes how the acoustic speech envelope of the stimulus is transformed into neural responses. This is the inverse approach of the previously mentioned envelope reconstruction where analysis is done from EEG to stimulus.

We calculated a TRF for every electrode channel in every participant. The first signal processing steps are identical to the envelope reconstruction model starting with downsampling to 1024 Hz, artefact rejection with MWF and filtering (0.5-8 Hz). Next, TRFs were calculated using the boosting algorithm (David et al., 2007; Brodbeck et al., 2018) with an l2 error norm (using the Eelbrain source code (Brodbeck, 2017)) as described in detail by David et al. (2007). After calculation, the TRFs were convolved with a rotationally symmetric Gaussian kernel of 5 samples long (SD=2). To analyze the TRFs in the time domain, we investigate the latency and amplitude of the negative and positive peaks occurring directly after the stimulus onset (Ding and Simon, 2011; Obleser and Kotz, 2011; Ding and Simon, 2012; Ding et al., 2014).

2.6 Experimental setup

Recordings were made in a soundproof and electromagnetically shielded room. Speech was presented bilaterally at 60 dBA and the setup was calibrated using a 2cm^3 coupler of the artificial ear (Brüel & Kjær 4152, Denmark) for each stimulus. The stimuli were presented using APEX 3 (Francart et al., 2008), an RME Multiface II sound card (Germany) and Etymotic ER-3A insert phones (Illinois, USA). First the participants did a behavioral test to measure their speech intelligibility. Next, a 64-channel BioSemi ActiveTwo (the Netherlands) EEG recording system was used for the EEG recordings at a sample rate of 8192 Hz. Participants sat in a comfortable chair and were asked to move as little as possible during the recordings. We inserted a small break between the behavioral and the EEG part and between the Matrix sentences and the story if necessary.

2.7 Statistical Analysis

Statistical analysis was performed using MATLAB (version R2016b) and R (version 3.3.2) software. The significance level was set at α=0.05 unless otherwise stated.

For the behavioral tests and envelope reconstruction we compared dependent samples (e.g. test-retest) using a nonparametric Wilcoxon signed-rank test. For every filter band and stimulus we tested the correlation between envelope reconstruction and speech intelligibility using Spearman's rank correlation. Next, we assessed the relationship between speech intelligibility, envelope reconstruction, filter band and stimulus by constructing a linear mixed effect (LME) model with the following formula:

$$corr \sim SI + stimulus + band + SI : band + SI : stimulus + SI : band : stimulus$$

where *corr* is defined as the Spearman correlation between the reconstructed and the acoustic envelope, with random effect of intercept of the participants and fixed and interaction effects of *SI* (speech intelligibility), *stimulus* (Matrix sentences or natural story) and *band* (the delta or theta filter band). As a control, we constructed the exact same model, but in function of SNR instead of SI.

To control if every chosen fixed and random effect benefited the model the Akaike Information Criterion (AIC) was calculated. The model with the lowest AIC was selected and its residual plot was analyzed to assess the normality assumption of the LME residuals. Unstandardized regression coefficients (beta) with 95% confidence intervals and p-value are reported in the results section.

To investigate which part of the TRF was significantly different from zero, we conducted a cluster-based permutation test. To explore significant differences between stimuli we conducted a positive and negative cluster-based analysis with a post hoc Bonferroni adjustment to correct for the positive and negative test. These tests are explained in detail by Maris and Oostenveld (2007). Spearman's rank correlation was used to investigate the possible change of amplitude and latency of the temporal-occipital peaks over time.

3 RESULTS

3.1 Behavioral speech intelligibility

During the experiment we measured speech intelligibility behaviorally at different SNRs for every participant. Figure 2 shows that the natural story (rating method) was significantly more difficult than the Matrix sentences (recall method) ($p<0.001$, CI(95%) = [15.99; 23.34], n=19, Wilcoxon signed-rank test). This indicates that the same SNR does not result in the same level of speech intelligibility for the different stimuli. To be able to compare the coherent story with the Matrix sentences, we need to account for this.

To check whether the used method to measure speech intelligibility, rate (story) versus recall (Matrix sentences), did not influence the results, we asked 9 of the participants to rate their speech intelligibility for the Matrix sentences, similar to the story, in addition to the standardized recall method. Comparing their rate and recall scores for the same Matrix sentences at 3 SNRs did not reveal any significant difference (-9.5 dB SNR: p=0.19, CI(95%)=[-11.50; 22.00]; -6.5 dB SNR: p=0.06, CI(95%)=[-29.50; 1.50]; -3.5 dB SNR: p=0.41, CI(95%)=[-9.00; 2.75]; n=9, Wilcoxon signed-rank test).

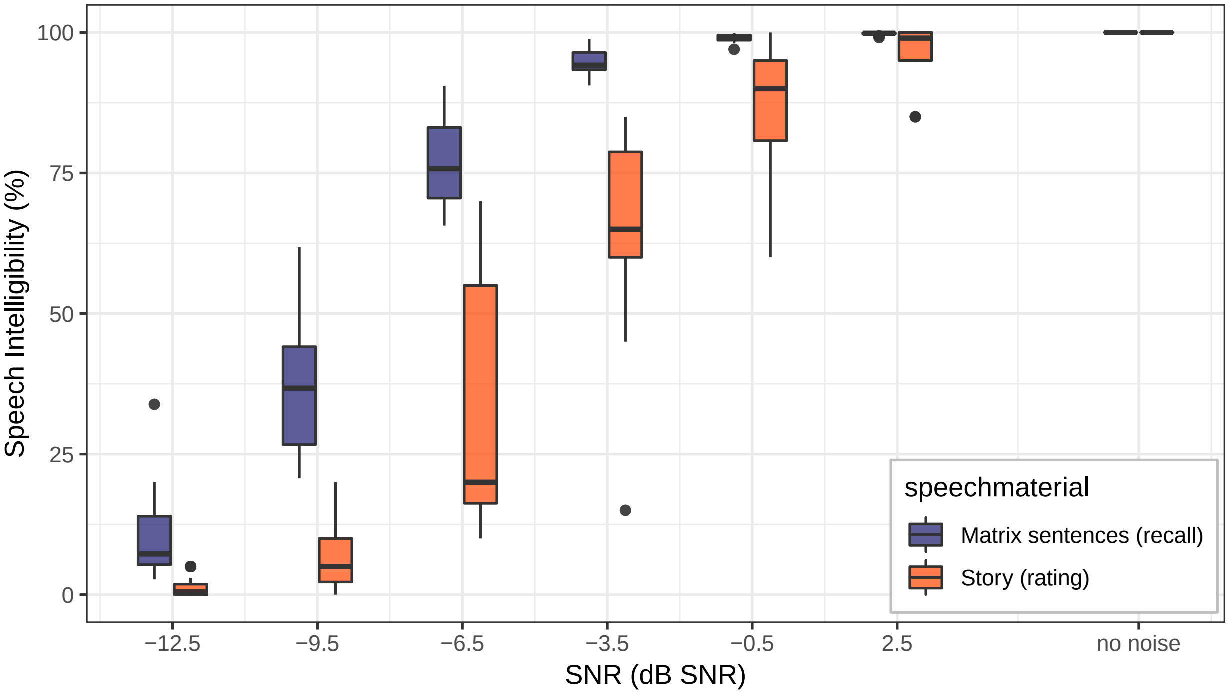


Figure 2. A comparison between the Matrix sentences and the story reveals that the story is more difficult to understand when adding background noise.

3.2 Envelope reconstruction

To measure neural envelope tracking, we calculated the Spearman correlation between the reconstructed envelope and the acoustic envelope. A test-retest analysis showed no significant difference between test and retest correlations (p=0.746, CI(95%) = [-0.004; 0.006], Wilcoxon signed-rank test), therefore we averaged the correlation of the test and retest conditions resulting in one correlation per participant per SNR per stimulus. We also conducted a chance level analysis to investigate whether there is a difference in chance level between both stimuli. A difference in chance level would imply that the decoder would show a preference to one of the two stimuli. To obtain the chance level we reconstructed the envelope of the story similar to the standard analysis. Next we correlated the reconstructed envelope of each story trial with the acoustic envelope of all trials of both the story (except for the used trial) and the Matrix sentences. No significant difference was found between the chance level of the stimuli (p=0.534, CI(95%)=[-0.005; 0.003], Wilcoxon

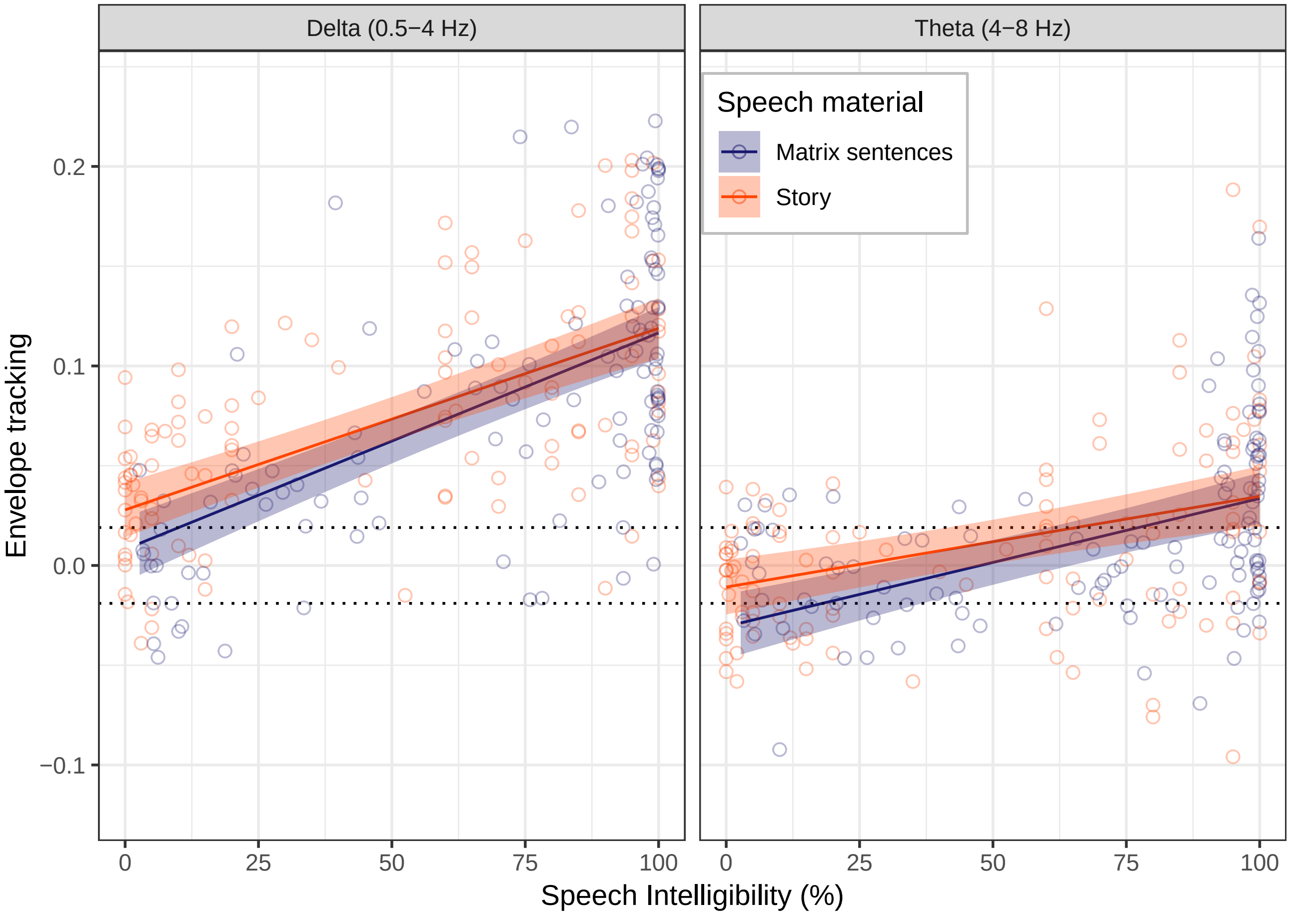


Figure 3. Neural envelope tracking increases with increasing speech intelligibility and by using natural speech as a stimulus. The shading represents two times the standard error of the fit and the dotted line is the significance level of the correlation (±0.019).

signed-rank test). In addition, the 95% confidence interval of the difference between the chance level of the stimuli is similar to the test-retest variability (CI(95%)=[-0.005; 0.006]), indicating that there is no important effect.

We analyzed neural envelope tracking in the delta (0.5-4 Hz) and the theta (4-8 Hz) band for the Matrix sentences and the natural story at various levels of speech intelligibility. Figure 3 shows that when speech intelligibility increases, the correlation between the acoustic and the reconstructed envelope, i.e. neural envelope tracking, increases for every filter band and every stimulus tested ($p<0.001$, table 1, Spearman rank correlation).

To additionally investigate the influence of stimulus choice, we created an LME model as a function of speech intelligibility. The analysis shows that neural envelope tracking is enhanced for the story compared to the Matrix sentences (fixed effect stimulus, p=0.010, LME, table 2). This enhancement does not significantly depend on the level of speech intelligibility or filter band (interaction effect SI:stimulus, p=0.155; interaction effect SI:band:stimulus, p=0.912; LME, table 2). Further, neural envelope tracking in the delta band (0.5-4 Hz) is higher than in the theta band (4-8 Hz) (fixed effect band, $p<0.001$, LME, table 2) with a steeper slope in the delta band (0.5-4 Hz) (interaction effect SI:band, $p<0.001$, LME, table 2).

When conducting the same analysis using SNR as a predictor for speech intelligibility, the same fixed and interaction effects were found to be significant as for the SI analysis (table 3). This shows that even at the same SNR neural envelope tracking for the natural story is enhanced compared to the Matrix sentences, making it impossible to disentangle between the effects of SNR and SI with the current data.

3.3 Temporal response function

The analysis above integrates all different time lags and channels to obtain an optimal reconstruction of the envelope and requires a decoder trained on a separate story. In the following analysis we focus on how the neural responses follow the envelope in the time and spatial domain and remove the assumption that neural processing is similar for the decoder story and the test stimuli by investigating TRFs. TRFs were calculated on an individual level. This resulted in 868 TRFs per participant (64 channels x 2 stimuli x 7 SNRs). To visualize topographies, we averaged the TRFs per stimulus per SNR over participants. To investigate the time-course of the TRFs, we averaged TRFs for a temporal-occipital channel selection (Figure 4). This selection is based on the TRF results shown in Figure 5. A cluster-based permutation test (Maris and Oostenveld, 2007) shows the TRF samples significantly different from zero, highlighted in bold in Figure 6.

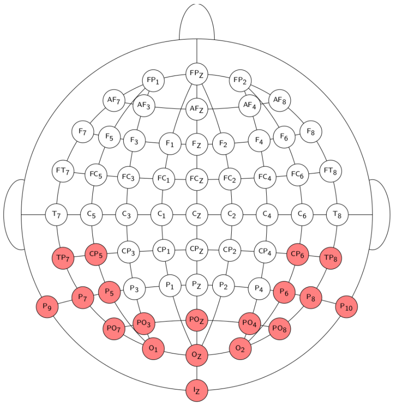


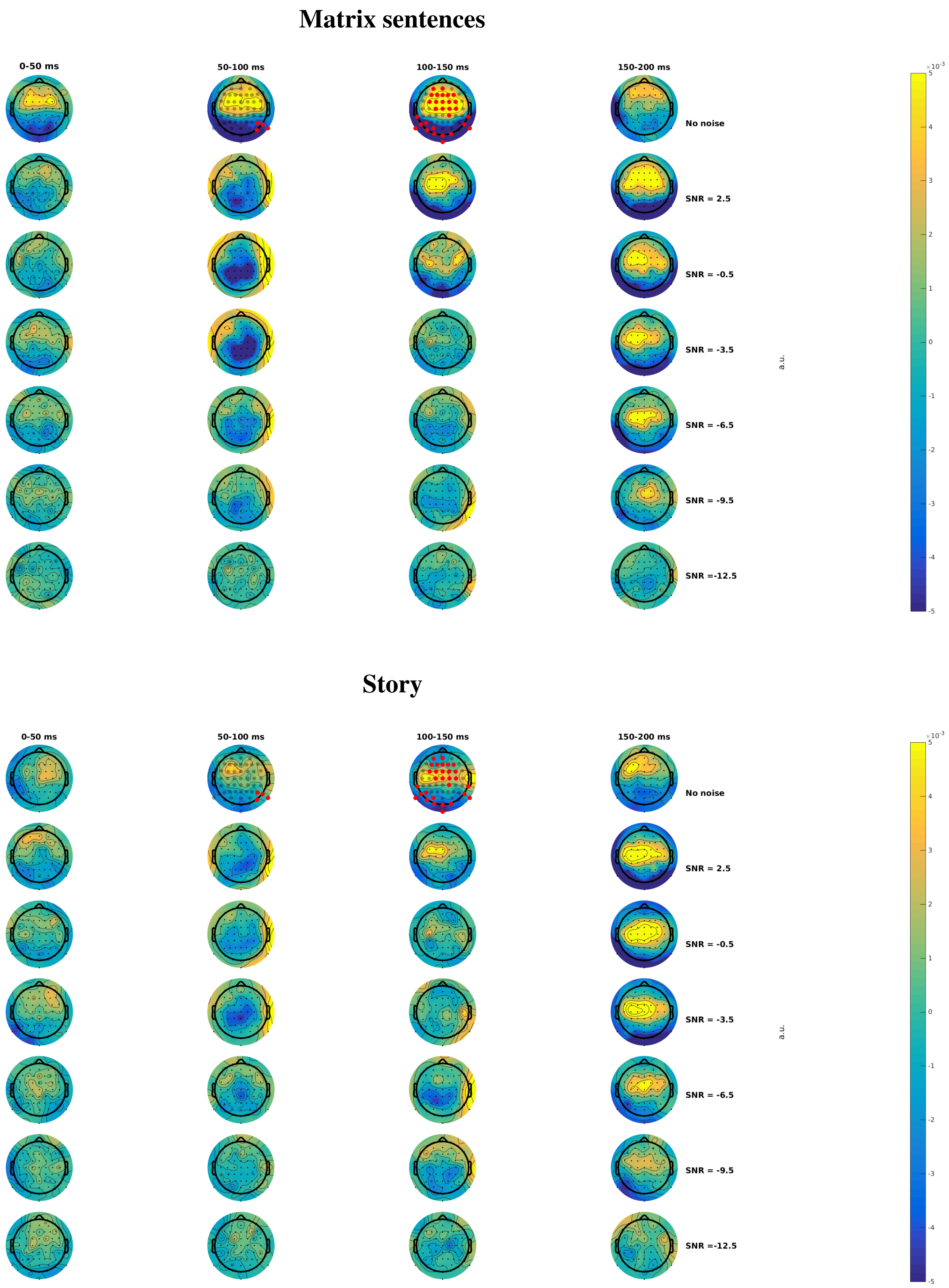
Figure 4. Electrode selection: 64 active electrodes placed according to the 10-20 electrode system. The locations of the electrodes that were selected for the calculation of the occipital-temporal TRF are indicated in red.

3.3.1 Effect of SNR on TRF

Figure 5 shows the spatiotemporal activation profile of respectively the Matrix sentences and the natural story. In the no-noise condition both stimuli show positive central and negative parieto-occipital amplitudes over time. When a small amount of noise is added and speech intelligibility remains almost unchanged from the no-noise condition (SNR=2.5 dB SNR; Matrix sentences: median SI=99.9%, sd=0.2; Story: median SI=99.0%, sd=4.7), the amplitudes across the entire scalp decrease between 0 to 150 ms, while amplitudes between 150 to 200 ms increase in both stimuli. Between 50 and 100 ms amplitudes even swap polarities.

When more noise is added and speech intelligibility decreases positive central and negative parieto-occipital activation decreases, especially in the 150 tot 200 ms timelag (Figure 5). In the 50 to 100 ms timelag, on the other hand, the negative central activation increases with decreasing speech intelligibility and reaches a maximum at SNR=-3.5 dB SNR.

To zoom in on the amplitude changes over time, we visualized an average TRF for the temporal-occipital channels per SNR in Figure 6. When speech intelligibility is very low (SNR<-12.5 dB SNR) both stimuli have very low responses over time. When speech is understood


Matrix sentences

Story

Figure 5. Topographies for the story and the Matrix sentences at different SNRs and different time lags varying from 0 until 200 ms. Significant differences between the Matrix sentences and the story are highlighted in red.

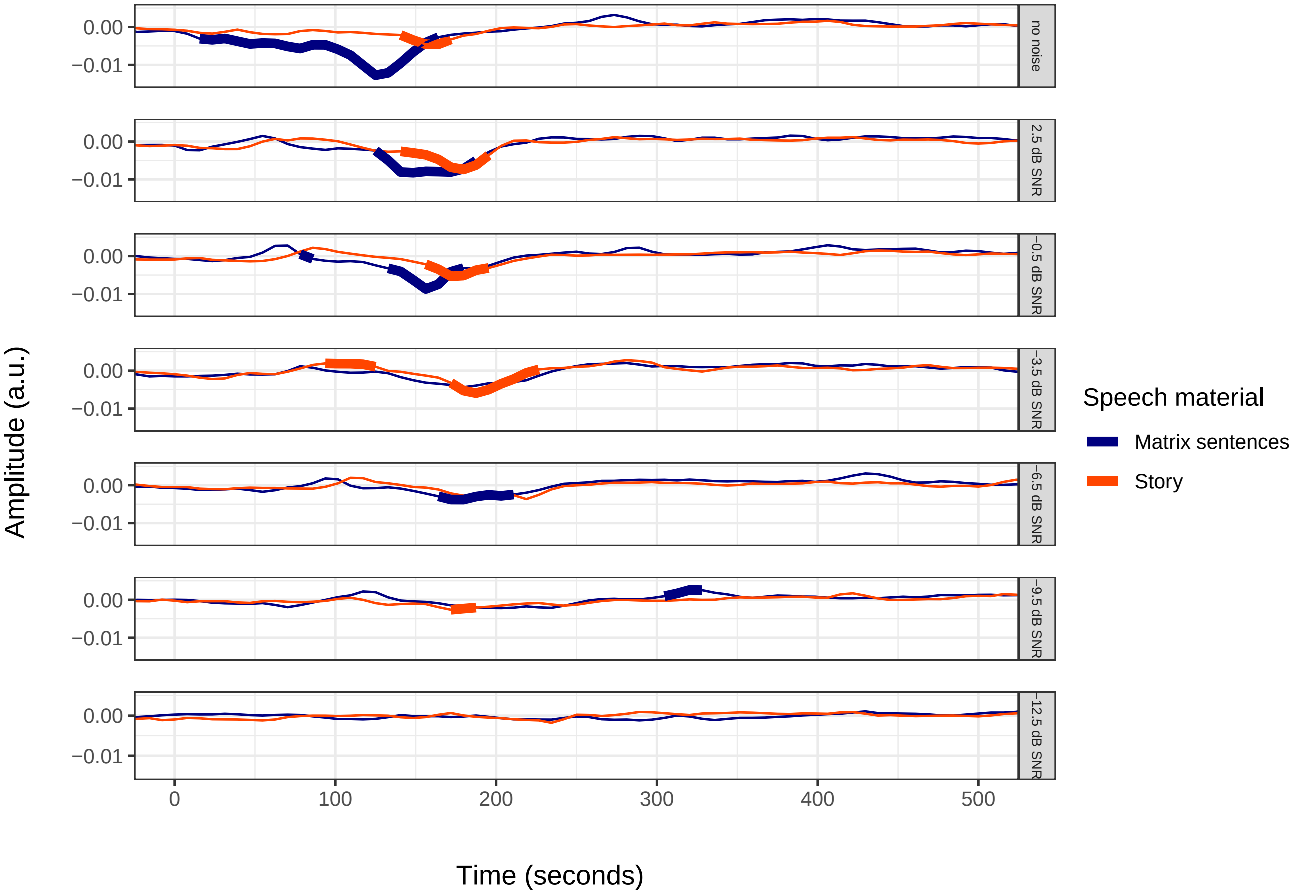


Figure 6. Time-course of the temporal-occipital TRFs over participants for the Matrix sentences and the story. TRF samples significantly different from zero are highlighted in bold.

a negative peak can be found. Figure 7 shows the latency and amplitude results of this peak on a participant level over speech intelligibility. It was determined individually by selecting the most negative amplitude of the TRF between 50 and 300 ms. With decreasing speech intelligibility the amplitude of the negative peak per participant decreases for both stimuli (Matrix sentences: Spearman rank correlation=0.49, p<0.001; Story: Spearman rank correlation=0.26, p=0.005).

3.3.2 Effect of stimulus type on TRF

Besides the decreasing amplitude, latency also decreases for the Matrix sentences with decreasing speech intelligibility (Spearman rank correlation=0.46, p<0.001). For the natural story, on the other hand, latency is not significantly related to speech intelligibility (Spearman rank correlation=0.02, p=0.835)).

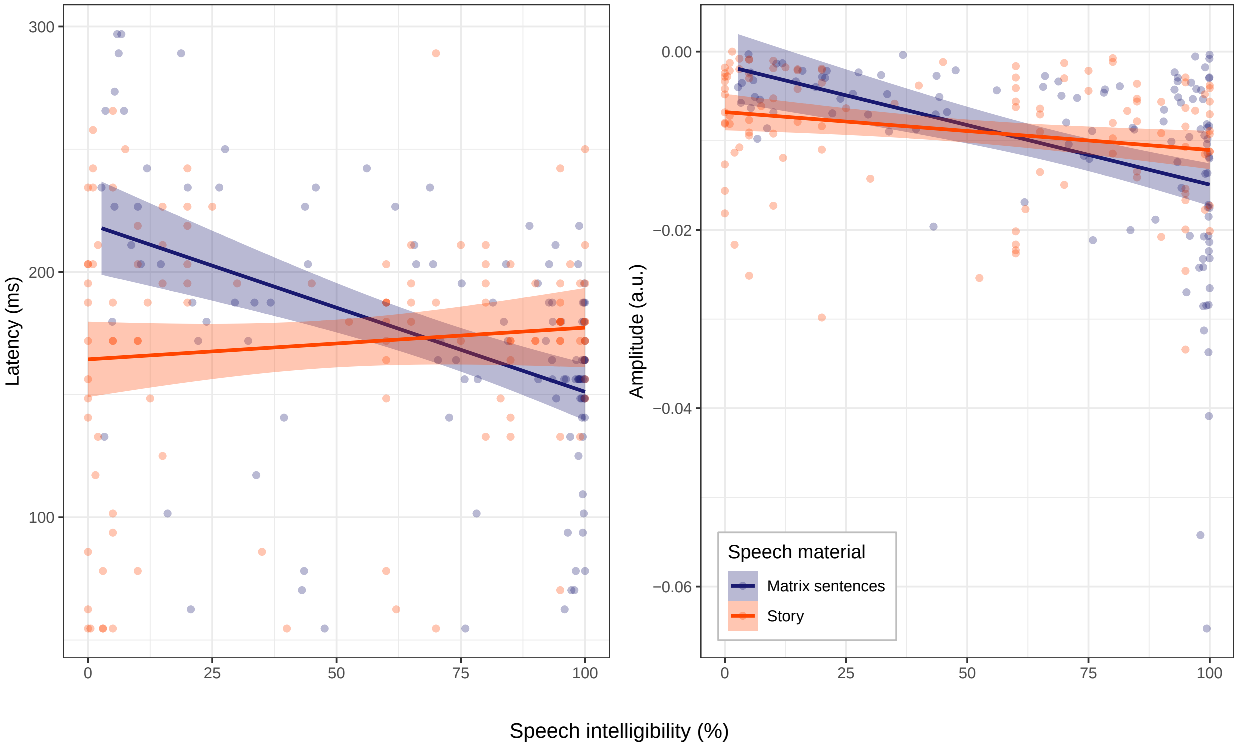


Figure 7. Latency and amplitude of the negative peak of the temporal-occipital TRF between 50 and 300 ms per participant over speech intelligibility.

Next to the difference between the Matrix sentences and the story concerning latency changes, other stimulus dependent differences can be found. First, a positive and negative cluster analysis (Maris and Oostenveld, 2007) over all participants revealed significant differences (α=0.025) between both stimuli in the no-noise condition with larger amplitudes for the Matrix sentences in the central and parieto-occipital channels, highlighted in red in Figure 5. In contrast to this stimuli driven difference in the no-noise condition, no significant differences between both stimuli could be found in the presence of background noise. Second, in addition to the prominent negative peak between 100 and 200 ms, a positive significant peak arises around 300 ms for the Matrix sentences at -9.5 dB SNR (Figure 6), while this is not the case for the story.

4 DISCUSSION

In this study we investigated whether the objective measure of speech intelligibility by Vanthornhout et al. (2018) using Matrix sentences can also be conducted with natural speech as this would be beneficial for clinical applications. To that end, we tested 19 normal-hearing participants. They listened to both the Matrix sentences and a natural story at varying levels of speech intelligibility while their EEG was recorded. We found that it is feasible to use natural speech as a stimulus for the objective measure of speech intelligibility and that noise and the stimulus type can change the temporal characteristics of the brain responses over the scalp.

4.1 The same SNR does not result in similar speech intelligibility for different stimuli

As a first step we measured speech intelligibility behaviorally for both stimuli at different noise levels. The results show that the same SNR does not result in similar speech intelligibility for the different stimuli. The story was found to be more difficult to understand than Matrix sentences. Although we controlled for the sex of the speaker and chose stimuli with similar speech rates and spectrum, the difference could still be due to different acoustic features such as for example prosody. The Matrix sentences namely are part of a standardized speech material where every word is spoken at the same intensity. The story, on the other hand, is narrated for children and has more variations. An additional reason to explain this difference is lexical prediction. Even though the permutations of the words are different in each Matrix sentence, the words themselves are all equally likely and familiar to the participants, in contrast to the story. Perhaps drawing from a larger pool of words for the Matrix sentences might have led to more similar intelligibility ratings between stimuli. Finally, speech intelligibility for both stimuli was measured in a different way: rating (story) versus recall (Matrix sentences). Similar to the rating and recall results for the Matrix sentences of Decruy et al. (2018), we did not find a statistical difference between both measuring methods applied on the same Matrix sentences.

4.2 Neural envelope tracking as an objective measure of speech intelligibility

We found that the correlation between the reconstructed and the acoustic envelope increased with speech intelligibility for both the Matrix sentences and the story. This supports the results of Luo and Poeppel (2007); Ding and Simon (2013); Ding et al. (2014); Molinaro and Lizarazu (2017); Vanthornhout et al. (2018); Lotzov and Parra (2019) where an increase in speech intelligibility was also found to accompany an increase in envelope tracking and demonstrates that the objective measure of speech intelligibility using Matrix sentences by Vanthornhout et al. (2018) can be conducted with fully natural speech.

Next, the tracking results in the delta band were significantly higher than in the theta band while the significance levels remain the same, resulting in a steeper slope of envelope tracking as a function of speech intelligibility in the delta band. This difference in correlation magnitude between the frequency bands could be explained by the fact that the modulation spectrum of both stimuli has most energy in the delta band (Luo and Poeppel, 2007; Aiken and Picton, 2008).

When investigating the differences between both stimuli, we found that the use of natural speech enhanced neural envelope tracking compared to Matrix sentences. This suggests that neural envelope tracking might capture the interaction between the incoming acoustic speech stream and top-down information (Hickok and Poeppel, 2007; Gross et al., 2013) such as for example semantic processing (Di Liberto et al., 2018; Broderick et al., 2018). A potential confound is that we used different SNRs for the two stimulus types (to control for intelligibility). This means that the differences in envelope tracking could be related simply to SNR rather than other stimulus properties. To investigate this, we conducted the same analysis, but with SNR as predictor instead of intelligibility, and again found significantly increased envelope tracking for the story stimulus. This shows that SNR by itself does not account for the full difference between the two stimulus types. However, apart from different SNRs, other confounding factors could be present where we cannot control for. First, although the acoustics of the stimuli were matched in terms of sex and speech rate of the speaker and spectrum of the stimulus, acoustic differences like prosody are still present, as discussed in paragraph 4.1.

Second, despite the questions asked to motivate the participants, the reduced correlations for the Matrix sentences could be linked to attention. Because listening to concatenated sentences can be boring, attention loss could occur which reduces neural envelope tracking (Ding and Simon, 2012; Kong et al., 2014; Petersen et al., 2017; Vanthornhout et al., 2019). For the natural story, on the other hand, attention could be less of an issue as attending this speech is entertaining possibly resulting in higher correlations.

4.3 The effect of noise and stimulus type on neural envelope tracking

In addition to envelope reconstruction to show the feasibility of natural speech as a stimulus for the objective measure (4.2), we conducted a TRF analysis. This analysis enables us to investigate the temporal characteristics of the brain responses over the entire scalp and removes the assumption that neural processing is similar for the decoder story and the test stimuli. The topographies in Figure 5 of both stimuli show a negative activation in the temporal-occipital channels and positive activation in the central channels. This is a typical topography of auditory evoked far-field potentials (Picton, 2011). The large negative peak within the 100 to 200 ms time lag (Figure 6) could be the so-called N100, usually occurring at a latency between 70-150 ms (Picton, 2011).

4.3.1 Effect of SNR and speech intelligibility on TRFs

Generally we found, similar to envelope reconstruction, high TRF amplitudes over the entire scalp when speech intelligibility is high (SI=100%) and reduced amplitudes when speech intelligibility decreased for both stimuli, again showing feasibility of natural speech as a stimulus for the objective measure of speech intelligibility. Most remarkable are the TRF amplitudes between 150 to 200 ms, which consistently decrease with decreasing speech intelligibility, perhaps indicating a time window sensitive to speech intelligibility. Another peculiarity are the noise induced topographic changes. When a small amount of noise is added and speech intelligibility remains almost unchanged from the no-noise condition (SNR=2.5 dB SNR; Matrix sentences: SI=99.9%; Story: SI=99.0%), TRF amplitudes across the entire scalp decrease between 0 to 150 ms, while amplitudes between 150 to 200 ms increase. Moreover, TRF amplitudes between 50 and 100 ms even switch polarities in the presence of noise. These results possibly reveal noise induced changes related to enhanced attention and listening effort (Ding and Simon, 2012; Kong et al., 2014; Petersen et al., 2017; Obleser and Kotz, 2011).

4.3.2 Effect of stimulus type on TRFs

Stimulus related differences can be found when comparing topography results between both stimuli. TRF amplitudes are larger for the Matrix sentences in the central and parieto-occipital channels compared to the story in the no-noise condition. In the presence of background noise, even at a very high SNR, no significant difference can be found anymore. A possible hypothesis could be the interaction between the incoming acoustic speech stream and top-down information (Hickok and Poeppel, 2007; Gross et al., 2013): In the no-noise condition Matrix sentences are mainly processed in a feed-forward acoustical way. The enhanced TRF amplitudes could be caused by the fixed syntactical 5-word structure of the Matrix sentences, resulting in a more rigid word and sentence rate compared to the story. However, when noise is added, more effort has to be paid to listen to the Matrix sentences. This changes listening to the Matrix sentences from a bottom-up process to an interactive bottom-up and top-down process similar to the story, diminishing the differences between both stimuli.

Another stimulus related difference is the latency pattern over speech intelligibility. The latency of the N100 peak decreases with increasing speech intelligibility for the Matrix sentences, while the latency remains unchanged for the story. A latency decrease with increasing speech intelligibility, similar to the Matrix sentences, has been reported in literature by Petersen et al. (2017) and Kong et al. (2014), but is not supported by Ding and Simon (2012). This different pattern between the Matrix sentences and the story could be explained by two factors. (1) Top-down processing: This is present for the story the entire time, for the Matrix sentences, on the other hand, it increases with increasing noise level. Top-down processing requires more time, which could result in delayed TRFs. (2) Attention: Listening to concatenated Matrix sentences might be boring, especially when speech intelligibility decreases, which could result in attention loss and less listening effort known to delay neural processing of speech (Ding and Simon, 2012; Kong et al., 2014; Petersen et al., 2017; Vanthornhout et al., 2019).

A last result to point out is the positive peak around 300 ms for the Matrix sentences at -9.5 dB SNR (SI=49%) (Figure 6). P300 can occur when a participant tries to detect a target stimulus (Picton, 1992, 2011). As the Matrix sentences do not contain semantic context, which makes content questions not possible, counting questions were asked at every SNR trial, for example, 'Which colors of boats were mentioned?'. We hypothesize that the question type, content questions for the story versus counting questions for the Matrix sentences, accounts for this P300 difference. As a consequence, the type of questions to ask is also an important factor to take into account for future research.

4.4 Implications for the objective measure of speech intelligibility

In this study we showed that the objective measure of speech intelligibility by Vanthornhout et al. (2018) using Matrix sentences can also be conducted with natural speech as a stimulus. This paves the way towards intelligibility measurements of any speech fragment, which is impossible today using behavioral measurements but may relate better to everyday communication and would be beneficial for clinical applications. In addition, we found an enhancement in neural envelope tracking when using natural speech as a stimulus instead of Matrix sentences. This suggests that neural envelope tracking might reflect the integration of incoming acoustic features and top-down information, which indicates that the choice of the stimulus has to be considered based on the intended purpose of the measurement. To conduct research, for example, and investigate neural speech processing in noise, a story could be an interesting choice as neural envelope tracking is more pronounced because of better sustained attention, more listening effort and/or semantic processing. However, when comparing speech intelligibility outcomes in a clinical setting, for example to fit hearing aids, top-down processing effects are undesired and should be ruled out and the Matrix sentences could be used instead.

4.5 Conclusion

We found increasing neural envelope tracking with increasing speech intelligibility for both stimuli with an additional enhancement for natural speech compared to Matrix sentences. These results show (1) the feasibility of natural speech as a stimulus for the objective measure of speech intelligibility, (2) that neural envelope tracking is enhanced using a story compared to Matrix sentences and (3) that noise and the stimulus type can change the temporal characteristics of the brain responses.

Table 1. Spearman rank correlation between neural envelope tracking and speech understanding

Speechmaterial	Filter band	Correlation	p-value
Matrix sentences	Delta (0.5-4 Hz)	0.62	$p<0.001$
Natural story	Delta (0.5-4 Hz)	0.59	$p<0.001$
Matrix sentences	Theta (4-8 Hz)	0.46	$p<0.001$
Natural story	Theta (4-8 Hz)	0.41	$p<0.001$

Table 2. Linear Mixed Effect Model of envelope reconstruction in function of SI

Linear mixed effect model (factor)	beta value	CI(95%)	p-value
Fixed effect SI	1.08×10^{-3}	$\pm 1.90 \times 10^{-4}$	$p<0.001$
Fixed effect stimulus	1.97×10^{-2}	$\pm 1.49 \times 10^{-2}$	$p=0.010$
Fixed effect band	-3.87×10^{-2}	$\pm 1.41 \times 10^{-2}$	$p<0.001$
Interaction effect SI:stimulus	-1.74×10^{-4}	$\pm 2.39 \times 10^{-4}$	$p=0.155$
Interaction effect SI:band	-4.43×10^{-4}	$\pm 2.14 \times 10^{-4}$	$p<0.001$
Interaction effect SI:band:stimulus	-1.28×10^{-5}	$\pm 2.25 \times 10^{-4}$	$p=0.912$

Speech Intelligibility (SI), Confidence Interval (CI)

Table 3. Linear Mixed Effect Model of envelope reconstruction in function of SNR

Linear mixed effect model (factor)	beta value	CI(95%)	p-value
Fixed effect SNR	7.75×10^{-3}	$\pm 1.39 \times 10^{-3}$	$p<0.001$
Fixed effect stimulus	-1.25×10^{-2}	$\pm 1.06 \times 10^{-2}$	$p=0.022$
Fixed effect band	-8.10×10^{-2}	$\pm 1.06 \times 10^{-2}$	$p<0.001$
Interaction effect SNR:stimulus	-1.01×10^{-3}	$\pm 1.83 \times 10^{-3}$	$p=0.284$
Interaction effect SNR:band	-3.20×10^{-3}	$\pm 1.83 \times 10^{-3}$	$p<0.001$
Interaction effect SNR:band:stimulus	-1.40×10^{-6}	$\pm 2.13 \times 10^{-3}$	$p=0.999$

Speech-to-Noise Ratio (SNR), Confidence Interval (CI)

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