Evidence for enhanced neural tracking of the speech envelope underlying age-related speech-in-noise difficulties

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Running head: Envelope tracking and speech perception across the lifespan

Abstract

When we grow older, understanding speech in noise becomes more challenging. Research has demonstrated the role of auditory temporal and cognitive deficits in these age-related speech-in-noise difficulties, beyond peripheral hearing loss. To better understand the neural mechanisms underlying these difficulties, we recruited young, middle-aged and older normal-hearing (NH) adults, and investigated the interplay between speech understanding, cognitive skills and neural tracking of the speech envelope using electroencephalography (EEG). The stimuli consisted of natural speech masked by speech-weighted noise or a competing talker, presented at several subject-specific speech understanding levels. The results show that healthy aging resulted in a quadratic increase in the speech reception threshold, i.e., worse speech understanding, most pronounced for the competing talker. Similarly, advancing age was associated with a quadratic increase in envelope tracking with a pronounced enhancement for older adults. Additionally, envelope tracking was found to increase with speech understanding, and this was most apparent for older adults. Since the cognitive tests partly explained the variability in envelope tracking, our results support the hypothesis that enhanced envelope tracking in older adults are the result of the activation of a larger number of brain regions for processing speech, compared to younger adults. From a cognitive perspective, this could reflect the inefficient use of cognitive resources, often observed in behavioral studies. Interestingly, the opposite effect of age was found for auditory steady state responses at low modulation frequencies, suggesting a complex interplay of different neural mechanisms with advancing age.

Keywords:

- neural tracking of the speech envelope
- aging
- electrophysiology
- speech understanding

New & Noteworthy

We measured neural tracking of the speech envelope across the adult lifespan and found a quadratic increase in envelope tracking with age. Using a more ecologically valid approach than auditory steady state responses, we found that young, older as well as middle-aged normal-hearing adults showed an increase in envelope tracking with speech understanding. Moreover, this association appeared to be stronger for older adults.

Introduction

Although people live longer, the rapid aging of the world population has also major implications for the society such as the increased need for specialized health care (United Nations, 2017). One of the major burdens that adults over 60 years old typically experience is the increased difficulty to communicate, especially in situations with background noise (World Health Organization, 2015). Since speech-in-noise problems can result in social isolation and an increased risk for cognitive impairment such as dementia (Wayne and Johnsrude, 2015; Goman and Lin, 2018), it is important to develop adequate, auditory diagnostic tests and rehabilitation strategies to cope with this.

Currently, hearing aids are the most well known rehabilitation devices to handle these speech-in-noise difficulties. Although they can compensate for the typical decreased audibility in the high frequencies by amplifying the signal, it has been demonstrated that they do not fully restore speech understanding (Tremblay et al., 2003). In addition, it has been shown that the difficulties for older compared to younger adults, are more pronounced for speech embedded in a competing talker than for maskers such as stationary speech-weighted noise (Goossens et al., 2017; Helfer and Freyman, 2014). Hence, a growing body of research supports the role of additional factors underlying speech understanding problems beyond age-related hearing loss (CHABA, 1988; Humes et al., 2012; Martin and Jerger, 2005). As competing speech contains silent gaps, age-related temporal processing deficits have been suggested to play a role in speech-in-noise difficulties (Füllgrabe et al., 2015; Hopkins and Moore, 2011; Helfer and Vargo, 2009). Additionally, it is known that competing speech not only results in a spectro-temporal overlap, i.e., energetic masking, but also requires high-level cognitive processes to inhibit the masker. It is therefore not surprising that several studies have demonstrated an association between the age-related decline of cognitive functions and the increased difficulty on speech-in-noise tests (Janse and Jesse, 2014; Janse, 2012; Cahana-Amitay et al., 2015; Desjardins and Doherty, 2013; Füllgrabe et al., 2015; Gordon-Salant and Cole, 2016).

Whether the increased difficulty with informational maskers with advancing age is purely due to a deficient temporal processing or age-related cognitive decline, is difficult to examine, as these are closely intertwined (CHABA, 1988; Martin and Jerger, 2005; Humes et al., 2012). Although a combination of these factors and peripheral hearing loss are likely to underlie most speech understanding problems, more insight is still needed into the specific contribution of each factor. Different techniques can be used to disentangle these factors (reviews of Pichora-fuller and Souza, 2003, and Humes et al. (2012)). The most common and appropriate way is recruiting persons across the lifespan with audiometric thresholds within the normal range and screening them for cognitive impairment. In spite of this design, it remains very difficult to disentangle these factors when only administering behavioral tests (Humes et al., 2012; Schoof and Rosen, 2014). Therefore, a growing body of research is using objective techniques to investigate the neural changes of aging related to speech processing, which cannot be predicted from the audiogram.

With advancing age, anatomical changes occur along the whole auditory pathway, from the spiral ganglion neurons, mid brain up to the auditory cortex (Kraus and Anderson, 2013; Peelle and Wingfield, 2016; Cardin, 2016). Additionally, functional changes have been found such as the loss of connectivity between cortical brain regions and increased bilateral activity in regions outside the core speech processing network (Peelle et al., 2010; Wong et al., 2009; Davis et al., 2008; Cabeza, 2002). Since speech processing is a rapid, time-varying phenomenon, methods with a high time resolution, such as magneto- and electroencephalography (MEG and EEG), are required to accurately investigate this (Lopes da Silva, 2013). In recent years, studies using MEG or EEG have consistently shown a decrease in the amplitude of responses that are mainly generated in the brain stem with advancing age (Bidelman et al., 2014; Anderson et al., 2012; Presacco et al., 2016b; Goossens et al., 2016; Leigh-Paffenroth and Fowler, 2006). For the cortex on the other hand, no general consensus has been found yet. In most research, higher response amplitudes have been observed during the presentation of non-speech sounds or short syllables (Bidelman et al., 2014; Sörös et al., 2009; Tlumak et al., 2015). Goossens et al. (2016) for example, found higher amplitudes for 4 Hz auditory steady-state responses (ASSRs) in normal-hearing (NH) older than young and middle-aged adults. Similarly, increased neural speech envelope tracking has been found for NH older adults (Presacco et al., 2016b). In contrast, studies have also shown a decrease in neural tracking of frequency modulated (FM) stimuli with advancing age (Henry et al., 2017) or no change for 20 Hz ASSRs (Goossens et al., 2016; Leigh-Paffenroth and Fowler, 2006; Grose and Mamo, 2010).

These controversial results are likely to be due to methodological differences. Researchers have been using different techniques but also diverse types of sounds such as clicks, frequency or amplitude modulated tones. Only recently, single-trial paradigms were used to measure neural tracking of the envelope of a continuous speech stimulus to study the processing of natural speech in noise (Kong et al., 2015; Ding and Simon, 2012; O'Sullivan et al., 2015; Das et al., 2016). To our knowledge, only one study has used a similar approach to investigate the effect of age. Presacco et al. (2016b) presented two stories to a group of young (18-27 years) and a group of older (61-73 years) NH listeners and instructed them to attend to one talker and ignore the other. The stories were presented at different signal-to-noise ratios (SNRs: quiet, +3, 0, -3 and -6 dB SNR). To measure the cortical tracking of the envelope, the envelope of the attended talker was reconstructed from MEG responses. Based on the correlation between the actual speech envelope and the reconstructed envelope, it was found that older adults had an enhanced cortical representation of the attended speech envelope compared to their younger counterparts. According to the authors, these results suggest a possible imbalance between inhibitory and excitatory processes or the loss of connections between different brain regions.

The benefit of the approach used by Presacco et al. (2016b) is that the stimulus closely resembles daily life speech and is only presented once, in a single-trial paradigm. Therefore, it is more ecologically valid than objective measures based on the responses to repeated, short, artificial stimuli, such as auditory brain stem responses (ABRs), cortical evoked responses or ASSRs. Additionally, envelope tracking measures can be used to objectively evaluate a person's speech understanding as there is ample evidence that the envelope is an important cue for speech perception (Shannon et al., 1995; Drullman et al., 1994) and studies have shown an increase in neural envelope tracking with increasing speech understanding for young NH participants (Ding and Simon, 2013; Vanthornhout et al., 2018; Kong et al., 2015; Peelle et al., 2013).

The present study was designed to further investigate the effect of age on neural envelope tracking and speech understanding in young, middle-aged and older NH adults by measuring envelope tracking using a single-trial and more ecologically valid method than ASSRs. Firstly, we expect, based on the results of Presacco et al. (2016b), to find enhanced envelope tracking with advancing age. In contrast to Presacco et al. (2016b), who compared MEG-responses of two extreme age groups, we also included middle-aged NH adults as it has been shown that speech understanding (Goossens et al., 2017; Helfer and Freyman, 2014) and cognitive function (Vercammen et al., 2016; Singh-Manoux et al., 2012) start to decrease from 45-50 years on. Secondly, we further extend the findings of Presacco et al. (2016b) by directly investigating the association between speech understanding and envelope tracking. Similarly to a recent study of Vanthornhout et al. (2018) conducted in young NH adults, we hypothesize to also find an increase in envelope tracking with speech understanding for middle-aged and older NH adults. To investigate this, participants are instructed to recall standardized sentences out loud during the EEG-recording. This way a more direct association between envelope tracking and speech understanding is ensured compared to previous studies in which neural responses are related to ratings or behavioral scores obtained before or after the EEG-recording (Ding and Simon, 2013; Vanthornhout et al., 2018; Anderson et al., 2011; Goossens et al., 2018). Additionally, we not only presented sentences at highly intelligible fixed SNRs as Presacco et al. (2016b), but also presented the stimuli at several subject-specific SNRs to ensure a range of different speech understanding levels for each individual.

Material and Methods

Participants

To investigate the effect of age beyond age-related hearing loss and cognitive impairment, middle-aged and older adults were recruited through a screening across Flanders, Belgium. Adults with normal hearing in both ears were recruited, with no indication of cognitive impairment or learning disability. From the 84 adults aged older than 44 years, only 40 persons met the inclusion criteria. This was not unexpected since hearing declines from 40 years on, especially in men (Moore et al., 2014; International Organization for Standardization, 2000). Additionally, persons were also excluded when a lower score than 26/30 was obtained on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). Lastly, the medical history and the presence of learning disabilities were questioned because serious concussions, medication used to treat for example insomnia (Van Lier et al., 2004) as well as learning disabilities such as dyslexia are known to affect brain responses (Power et al., 2016; Poelmans et al., 2012; De Vos et al., 2017).

After screening, a total of 47 participants (11 men and 36 women) participated in the study. Their age ranged from 17 until 82 years (histogram of ages, see figure 1). All participants had Flemish as their mother tongue and were normal hearing in both ears (thresholds from 125 until 4000 Hz lower or equal to 30 dB HL; figure 2). A symmetrical hearing was ensured based on the criteria derived from the AMCLASS algorithm of Margolis and Saly (2008). Lastly, we examined the handedness and ear preference of our participants using a Flemish, modified version of the laterality preference inventory of Coren (1993) to choose the stimulation ear. This study was approved by the Medical Ethics Committee UZ KU Leuven / Research (reference no. S57102 (Belg. Regnr: B322201422186) and S58970 (Belg. Regnr: B322201629016)). All participants gave their written informed consent, and were paid for their participation if they were older than 35 years.

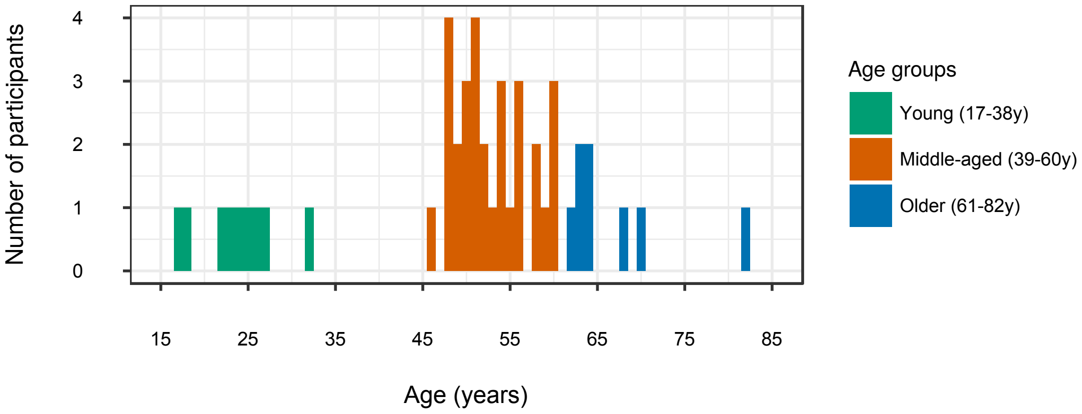

Figure 1: Distribution of the number of participants per age

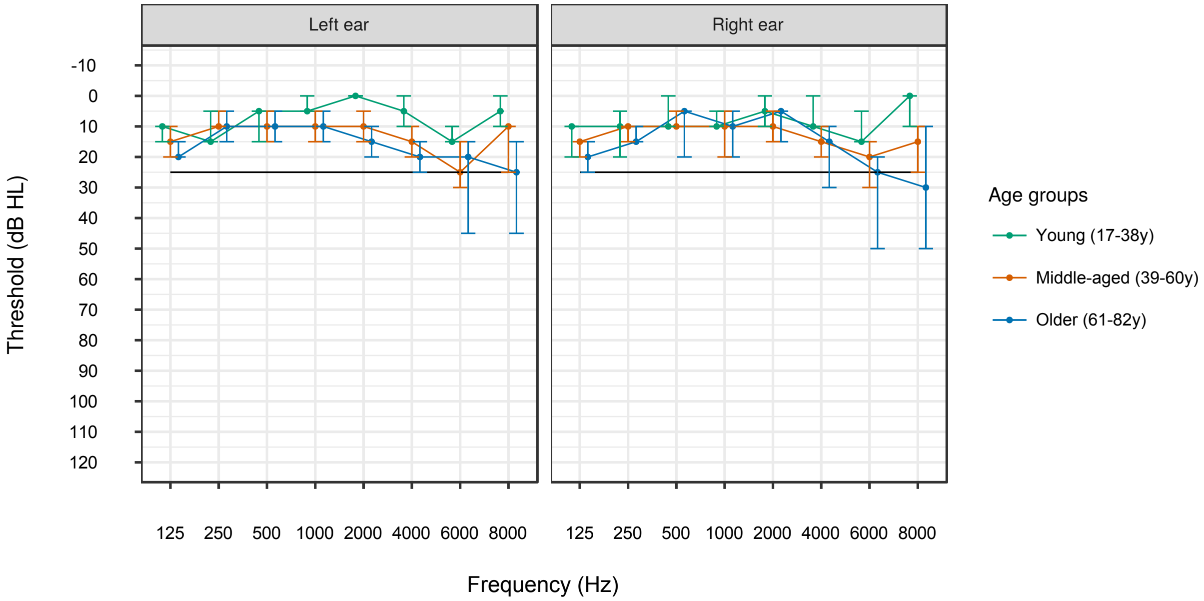

Figure 2: Median air conduction thresholds (in dB HL) of young, middle-aged and older participants. Error bars indicate the interquartile range.

Stimuli

For the behavioral and EEG experiment, we used the same target stimuli and maskers. Moreover, we presented Matrix sentences as well as a story to the participants because the structure of the Matrix sentences does not resemble daily life communication. Two maskers were chosen as previous studies have shown that the effect of age can be more detrimental for competing talkers than for purely energetic maskers. In addition to these stimuli, two other stimuli were used in the present study. Firstly, a story was presented to train the linear decoder used to reconstruct the speech envelope from the EEG (see Signal processing). Secondly, tone pips were presented to evaluate the effect of age on the responses to non-speech stimuli and to investigate if a similar effect of age can be found compared to responses to speech stimuli (see EEG experiment).

Target stimuli

In this study, we used the Flemish Matrix sentence test (Luts et al., 2014) to evaluate a participant's speech understanding behaviorally. The Matrix sentence test consists of 13 lists of 20 sentences where each sentence has a fixed syntax structure of 5 word categories "name, verb, numeral, color and object" (e.g. "Lucas draagt twaalf paarse boten" ("Lucas carries twelve purple boats")). During the test, participants are instructed to recall the heard sentence using a 5 x 11 matrix containing 10 possibilities for each word of the sentence as well as the option to give no answer. The percentage of correctly recalled words is used as a measure for speech understanding.

Although the Matrix sentences are translated into different languages to evaluate a person's speech understanding, the structure of these sentences does not resemble daily life communication. To get more insight in daily life speech understanding, we chose to also present commercial recordings of stories to our participants similar to studies investigating the cocktail party phenomenon (e.g. O'Sullivan et al., 2015; Das et al., 2016; Ding and Simon, 2012). The story that we used in this study is "De Wilde Zwanen" by Hans Christian Andersen, narrated by a female, Flemish talker and was 28 minutes long. The Story was set to the same root mean square level and spectrum as the Matrix sentences and silences were shortened to a maximum duration of 200 ms based on the results of a previous study (Decruy et al., 2018).

Maskers

To investigate how envelope tracking is affected by speech understanding, several levels of speech understanding were created by adding background noise. As shown before by Goossens et al. (2017) and Helfer and Freyman (2014), competing speech can have a more detrimental effect on speech understanding with advancing age compared to speech-weighted noise. As competing speech contains silent gaps, the listener could reconstruct the target more easily and achieve better speech understanding compared to a stationary masker (Festen and Plomp, 1990; Francart et al., 2011; Koelewijn et al., 2012). However, this potential benefit depends on the temporal processing ability of the listener which appears to deteriorate with healthy aging (Desjardins and Doherty, 2013; Füllgrabe et al., 2015). To investigate this, we examined the effect of both a stationary speech-weighted noise (SWN) and a competing talker (CT) on speech understanding in the present study. For the Matrix sentences as well as the Story, we created a SWN which had the same long-term-average spectrum as the target stimulus. This resulted in optimal spectral masking, also called energetic masking. For the informational masker, we used a second story, “Bianca en Nero” by Béatrice Deru-Renard which was narrated by a male, Flemish talker in contrast to our target stimulus. Similar to the target Story, the silences of the CT were shortened to 200 ms and the spectrum as well as the root mean square level were matched to the those of the target stimulus.

Set-up

Environment

In a first session, the behavioral experiments were conducted at the research group ExpORL from the KU Leuven or at home. For all participants, the second session took place at the research group to record the EEG in a triple-walled, soundproof booth, equipped with a Faraday cage to avoid electromagnetic interference.

Auditory stimulation

For the auditory stimulation, we used a laptop connected to a RME Hammerfall DSP Multiface II or RME Fireface UC soundcard (RME, Haimhausen, Germany), running the software platform APEX (Dept. Neurosciences, KU Leuven) (Francart et al., 2008). The target speech stimuli were presented monaurally through ER-3A insert phones (Etymotic Research, Inc., IL, USA) at an intensity of 55 dB SPL (A weighted). For all participants except one, stimuli were presented to the right ear. The maskers, SWN or CT, were presented to the same ear as the target stimulus and their levels were adjusted according to the chosen SNR. Before administering the experiments, all stimuli were first calibrated with a type 2260 sound level pressure meter, a type 4189 half-inch microphone and a 2cc coupler (Bruel & Kjaer, Copenhagen, Denmark).

EEG recording

To record the EEG, we used a BioSemi ActiveTwo system (Amsterdam, Netherlands), with 64 active Ag/AgCl electrodes and two extra electrodes, serving as the common electrode (CMS) and current return path (DRL), respectively. Electrodes were mounted in head caps containing electrode holders placed according to the 10-20 electrode system. The EEG recordings were digitized at a sampling rate of 8192 Hz and stored on a hard disk using the BioSemi ActiView software.

Experimental procedures

After screening, all participants first completed the behavioral experiment in which speech understanding in noise was evaluated for two speech materials, Matrix and Story, and two maskers, SWN and CT. The outcome of the speech-in-noise test was not only used to assess the effect of age on speech understanding but also to determine equivalent speech understanding levels across participants for the EEG experiment. In addition, two cognitive tasks were administered to investigate the contribution of working memory and inhibition. Finally, EEG was used to measure neural envelope tracking and get insight into the interplay between age, speech understanding and envelope tracking. An overview of the main procedures is depicted in figure 3.

Speech understanding in noise: behavioral experiment

During the Matrix sentence test, participants were instructed to recall sentences. An adaptive procedure was chosen to converge as quickly as possible to the speech reception threshold (SRT; SNR at which 50% speech understanding is achieved). For this test, the procedure of Brand and Kollmeier (2002) was used to adapt the level of the masker (Luts et al., 2014). To avoid confounds of procedural learning, two training lists of each 20 sentences were first administered. The Matrix sentences were presented in both SWN and CT and the order of presenting first SWN or CT was randomized across participants. The SRT was defined as the last SNR presented in a list of 20 sentences.

After the Matrix sentence test, we administered an adapted version of the self-assessed Békesy procedure (Decruy et al., 2018) to create equivalent speech understanding levels for the Story used during the EEG experiment. During this procedure, participants were provided with a scale from 0 to 100% to rate their speech understanding. Based on these ratings, the level of the masker was adapted until the procedure converged to the SRT. The procedure was administered at least twice and the SRT was determined as the average of the last presented SNR of these two runs. When the outcome of a run differed more than 3 dB with the previous, a third run was administered. In this case, the average of the last presented SNR of the second and third run was used as the SRT in order to exclude procedural learning effects.

To ensure comparable understanding levels for Matrix and Story as well as to avoid the confounds of rating biases, we used the difference in SRT between Matrix and Story on the self-assessed Békesy procedure (Decruy et al., 2018), further described as “Békesy procedure”, as an adjustment value. Consequently, the Story adjustedSRT per participant was calculated by subtracting this adjustment value from the SRT on the Matrix test (Figure 3). In the beginning of the study, the Békesy procedure was only administered in the presence of SWN. However, during the EEG recording of the first participants (13/47), we noticed that the difference in SRT between Matrix and Story was substantially larger when using CT as masker (i.e., more than two times the difference in SWN). Hence, for the remaining participants, the Békesy procedure was administered for both maskers. The Story adjustedSRT was first calculated based on the results in SWN and if the difference between Matrix and Story was substantially larger for CT compared to SWN, the Story adjustedSRT was adapted. While this led to differences across participants in the determination of the adjustment value, we do not believe that this influenced our results as we analyzed envelope tracking in function of the exact speech understanding percentages calculated or rated during the EEG experiment.

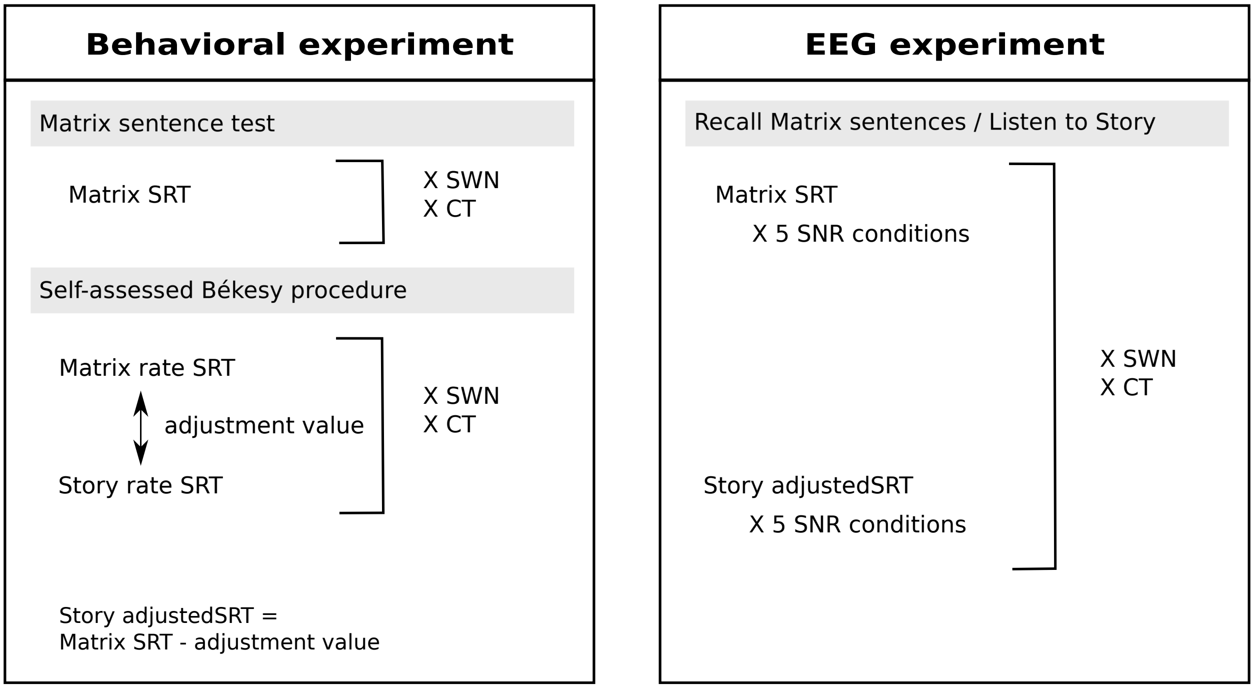

Figure 3: An overview of the main experiments conducted during the behavioral and EEG experiment.

Envelope tracking and cortical responses to tone pips: EEG experiment

For each participant, we started the EEG experiment with the tone pips. The tone pips were created using a sinusoid with a carrier frequency of 500 Hz and a total duration of 21 ms (4 ms on- and off-ramps). With an inter stimulus interval of 500 ms, repeating these tone pips resulted in a repetition frequency of approximately 1.92 Hz. In total, 250 tone pips were presented to each participant at an intensity of 90 dBpeSPL. After the tone pips, one block of the Matrix and one of the Story were presented, within each block all the different SNR conditions per masker (see table 1). Next, the story “Milan” that lasts 12 minutes and is written and narrated by Stijn Vranken, was presented without masker to have an optimal condition to create a linear decoder (see Signal Processing), followed by the remaining two blocks of the Matrix and Story. The order of the Matrix and Story was quasi-randomized across participants as well as the order of the maskers. For example, when the Matrix sentences were presented first in SWN, CT was used to mask the Story that preceded. Alternating the maskers kept the participants motivated.

Procedure for Matrix and Story

During the EEG experiment, the participants were seated in a comfortable chair. Participants were asked to recall the Matrix sentences out loud, trial-by-trial similar to the behavioral test. This way, their speech understanding score per condition could be determined and directly associated to the EEG responses. For the Story, persons were asked to actively listen and answer a question about the content to keep them alert. In addition, participants were also asked to rate their speech understanding for both Matrix and Story using the same scale as for the Békesy procedure. Based on the percentage correctly repeated words for the Matrix sentences, a direct association between envelope tracking and speech understanding could be investigated. For the Story, we adjusted the ratings of the participants by adding the difference score between the percentage correctly repeated words and the rated percentage for the Matrix sentences, per masker condition.

Table 1: Overview of the different Matrix and Story conditions for both maskers, presented during the EEG experiment (e.g. SNR at which a speech understanding (SU) score of 20% should be achieved: 20% SU). To avoid rating bias, we created the Story adjustedSRT (Figure 3).

	SWN		CT	
SNR	Matrix	Story	Matrix	Story
20% SU	SRT-3 dB	adjustedSRT-3 dB	SRT-4 dB	adjustedSRT-4 dB
50% SU	SRT	adjustedSRT	SRT	adjustedSRT
80% SU	SRT+3 dB	adjustedSRT+3 dB	SRT+4 dB	adjustedSRT+4 dB
95% SU	SRT+6 dB	adjustedSRT+6 dB	SRT+8 dB	adjustedSRT+8 dB
fixedSNR	No noise	No noise	0 dB SNR	0 dB SNR

As shown in table 1, we presented the Matrix sentences and Story at different specific SNRs to obtain a speech understanding score which could be directly associated to envelope tracking. We created four subject-specific SNR levels by lowering and raising the individual Matrix and Story adjustedSRT by one or two times 3 dB. This way, we could create equivalent, subject-specific speech understanding levels which covered the psychometric function of each individual (20%, 50%, 80%, 95% speech understanding). As can be inferred from table 1, a larger step size of 4 dB was used for CT since using fluctuating maskers results in less steeply psychometric functions compared to stationary maskers (Francart et al., 2011; Macpherson and Akeroyd, 2014). In addition to the subject-specific SNRs, two fixed SNRs across participants were presented. In the block where CT was the masker, we presented the target and competing talker at the same level, in other words, 0 dB SNR. In the SWN block, the target talker was also presented without any masker (No noise). For the Matrix sentences, a list of 20 sentences with a duration of 1.5 to 2.5 s per sentence was presented per SNR while the Story of 28 minutes was divided in 2 blocks of each 5 equal parts of approximately 3 minutes. Taken together, each participant completed for both the Matrix sentences and Story, 2 blocks representing the two maskers, which each consists of 5 conditions (i.e., 4 subject-specific SNRs + fixed SNR). The order of the SNRs within each block was randomized across participants.

Signal processing

All signal processing analyses were done off-line, using MATLAB R2016b.

Envelope reconstruction

In this study, we measured neural tracking of the speech envelope by calculating the correlation between the actual, acoustic speech envelope and the reconstructed envelope from the EEG response.

First, the speech envelope was extracted according to Biesmans et al. (2016) i.e., filtering the target speech stimulus using a Gammatone filterbank followed by a power law (Søndergaard and Majdak, 2013; Søndergaard et al., 2012). To decrease processing time, the acoustic envelope was downsampled in a first step from 48000 Hz to 256 Hz. Then a type 2, zero-phase Chebyshev filter (80 dB attenuation at 10% of the passband) from 1 up to 8 Hz was applied to the envelope. Finally, after filtering, the speech envelope was further downsampled to 128 Hz.

Similar to the acoustic envelope, the EEG data was first downsampled from 8192 Hz to 256 Hz. Next, a generic EEG artifact removal algorithm based on the multi-channel Wiener filter (MWF) was applied on the EEG-data (Somers et al., 2018). More specifically, the MWF was trained based on the data from the story "Milan" and then applied on the target stimuli, the Matrix sentences and story "De Wilde Zwanen". After artifact removal, the EEG-signals were re-referenced to the average of the 64 channels. Then the data was bandpass filtered using the Chebyshev filter similar to the acoustic envelope and downsampled to 128 Hz.

To measure neural envelope tracking, we used the stimulus reconstruction approach described by Vanthornhout et al. (2018). More specifically, the reconstructed envelope $\hat{s}(t)$ was obtained by applying a linear decoder on EEG signals. This decoder is a spatiotemporal filter that linearly combines the EEG signals of the different channels and their time shifted versions to optimally reconstruct the envelope. Mathematically, this can be formulated as follows: $\hat{s}(t) = \sum_n \sum_\tau g(n, \tau) R(t + \tau, n)$, with t the time ranging from 0 to T, n the index of the recording electrode ranging from 1 to 64 and τ the post-stimulus integration window length. We chose an integration window from 0 until 500 ms as it is shown that older adults have delayed responses (Tremblay et al., 2003; Presacco et al., 2016b; Anderson et al., 2012). The decoder was created using the mTRF toolbox (Lalor et al., 2006, 2009). More specifically, the weights of the decoder were determined in a training phase by applying ridge regression on the inverse autocorrelation matrix: $g = (RR^T)^{-1}(RS^T)$ with R as the time-lagged matrix of the EEG signal and S the speech envelope. The decoder g was trained for each participant on the story “Milan” and contained a matrix of 64 (EEG channels) x 65 (time delays; 500 ms) elements.

After training, a subject-specific decoder was applied on the EEG-data of the Matrix sentences and the story “De Wilde Zwanen”. The reconstructed envelope was calculated for each condition, i.e., each SNR, and then correlated with the actual envelope using the bootstrapped Spearman correlation by conducting a Monte Carlo sampling (Vanthornhout et al., 2018). A significance level of the correlation was calculated by correlating random permutations of the actual and reconstructed envelope (1000 times) and taking percentile 2.5 and 97.5 to obtain a 95% confidence interval.

Tone pips

The ASSRs evoked by the tone pips were analyzed as follows (Picton et al., 1987; Van Eeckhoutte et al., 2018; Vercammen et al., 2017; Goossens et al., 2016). First the EEG signal was re-referenced to the average of the 64 channels, high-pass filtered with a cutoff frequency of 0.5 Hz and segmented in epochs of 0.521s, containing exactly one presentation of the tone pip. To remove artifacts, 5% of the epochs containing the largest peak to peak amplitudes were rejected.

Next, denoising source separation (DSS) was applied using the epoched EEG data as input. DSS is an algorithm based on principal component analysis which designs a spatial filter that separates neural activity into stimulus-related and stimulus-unrelated components, based on a criterion of stimulus-evoked reproducibility (de Cheveigné and Simon, 2008). After applying DSS on the raw, filtered unepoched data, the EEG data was segmented again, but now in epochs of $\pm$ 2 s to ensure a good frequency resolution. In addition, artifacts were removed again by rejecting 5% of the epochs containing the largest peak to peak amplitudes before transforming the epochs into the frequency domain. A one-sample Hotelling T^2 test (with α = 0.05, Gransier et al., 2017; Hofmann and Wouters, 2012; Hotelling, 1931), was used to determine if the response amplitude differed significantly from the non-synchronized neural background activity (EEG noise). For our statistical analysis, we used the normalized SNR to one second as a measure for the size of the ASSR: $SNR(dB) = 10 \times log_{10}(\frac{\frac{P_{(S+N)}}{P_N}}{totalseconds})$ with P_N reflecting the power of the non-synchronized neural activity and $P_{(S+N)}$ reflecting the total power of the synchronized neural response to the tone pip and EEG noise in the frequency bin of interest (1.92 Hz).

Cognitive tests

The Flemish computerized version of the Reading Span Test (RST; Vercammen et al., 2016; van den Noort et al., 2008) and the paper version of the Stroop Test (Hammes, 1978) were used to evaluate working memory and inhibition. Although our participants were screened for cognitive impairment using the MoCA, studies have reported that even in a healthy aging population, cognitive function declines with age (Humes et al., 2012) and may be associated with increased cortical envelope tracking (Presacco et al., 2016a).

To assess working memory, participants were seated in front of a computer screen where a sentence was visually presented. Three sets of 20 sentences were administered, containing each 5 randomized subsets of 2, 3, 4, 5 or 6 sentences (Vercammen et al., 2016). The participants were instructed to read the sentences out loud. After reading a subset, the participants were asked to recall as many as possible of the sentence-final words of the previous subset. Additionally, they were also motivated to pay attention to the meaning of the sentences by asking three content questions.

The scores on the latter task were not included in their final score on 60 for the RST (Vercammen et al., 2016).

Lastly, a paper version of the Stroop Test (Hammes, 1978) was used to assess inhibition. Participants were presented three cards of which each card contained 10 rows of each 10 elements. On the first card, the color names "red, green, yellow and blue" were printed multiple times in black ink. Participants had to read these words as accurate and fast as they could, while their response time was recorded. On the second card, rectangles were presented in the same colors and participants had to name the color. As no inhibition was needed, this is called the congruent task. Lastly, a third, incongruent, card was presented where the color names were printed in a different color than it's meaning, e.g. the word "blue" colored red. The goal was to name the color of the words while inhibiting reading the words. The score on this test was calculated as the difference in response time (in seconds) between the third and second card. For means of visualization and interpretation of the results, the Stroop results will be analyzed by subtracting the difference score from the value "60" which is also the maximum score that can be obtained on the RST.

Statistical analysis

The statistical analyses were conducted using R software (version 3.4.4; nlme package - version 3.1-131.1; Field et al. (2012); Pinheiro et al. (2017)). The effect of age on the SRT and envelope tracking was analyzed using Linear Mixed-effect Models (LMMs) as we collected multiple measurements per participant (e.g. two masker conditions) and these models can handle missing data well (the data of this study contains 7 missing data points; Baayen et al., 2008). The fixed-effect part of the LMMs consisted of the predictors of interest whereas the random-effect part included the variable participant, nested in one of the repeated measures predictors if this improved the model's fit. Since no repeated measurements were conducted for the tone pips and cognitive tasks, the effect of age on these responses/scores was analyzed using Linear Fixed-effect Models (LFMs). All models were fitted using the maximum likelihood estimation.

The best fitting model was determined by first progressively introducing multiple fixed-effects and corresponding interactions. Then, the different models were compared using likelihood ratio tests and Akaike's Information Criterion (AIC; Akaike, 1974). The best fitting model served as starting point for the evaluation of the contribution of other predictors until the final best fitted model was determined. Significant main and interaction effects of the final model are discussed in the results section by reporting the unstandardized regression coefficient (β) with standard error (SE), t-Ratio and p-value per fixed-effect term. In all models, the predictors speech understanding and age were considered as continuous variables. To clearly visualize the interactions for envelope tracking at subject-specific SNRs, age was not plotted as a continuous variable in figure 5. Instead, three example regression lines representing a young (28), middle-aged (50) and older (71) person were fitted on the data. As the decline in auditory temporal processing is closely intertwined with the decrease in cognitive abilities with advancing age, we also used LMM's to assess if cognition has an additional effect on speech understanding in noise and envelope tracking, beyond age. A significance level of α = 0.05 was set for all the models unless otherwise stated (e.g. correction for multiple comparisons using the method of Holm, 1979).

Results

In this section, we first report the results of the behavioral speech understanding in noise experiment. Then, we investigate the association between speech understanding and envelope tracking, and the effect of age on envelope tracking and tone pip responses. Finally, we analyse the effect of age on cognition and the interplay between age, cognition, speech understanding in noise, and envelope tracking.

Speech understanding in noise

To assess the influence of age and masker on speech understanding in noise, we analyzed the SRTs of all participants obtained during the behavioral experiment. We can infer from figure 4 and the best fitted LMM that the SRT increased quadratically with advancing age ($p = 0.04$; table 2). In addition to this, our participants achieved a significantly lower, better SRT for CT compared to SWN ($p < 0.001$; table 2). Besides these main effects, we also detected a significant interaction between age and the type of masker, indicating a steeper increase in SRT with advancing age when CT was used as masker compared to SWN (p = 0.02; table 2). We noticed after data collection that 12/47 participants completed the behavioral experiment with stimuli (both masker and target) with maximal silence gaps of 300 instead of 200 ms. When running the analyses with the exclusion of these participants, the same effects remained significant.

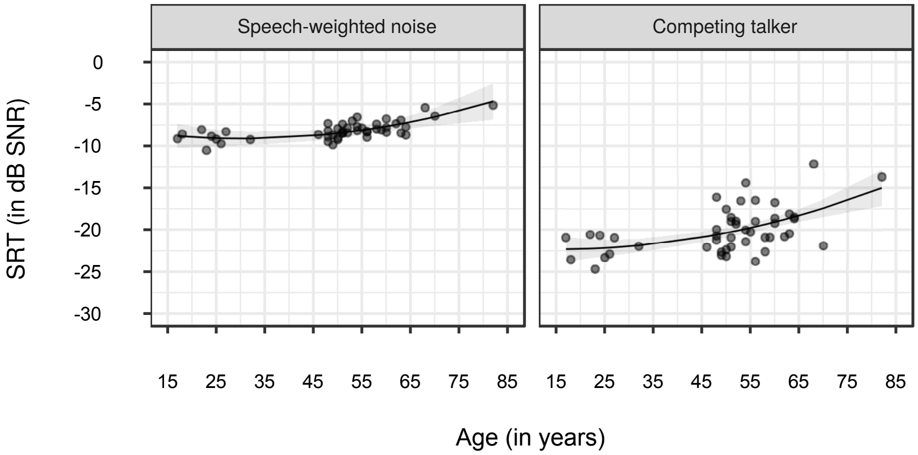

Figure 4: The speech reception threshold (SRT) for two masker types: speech-weighted noise (SWN) and a competing talker (CT) across the adults lifespan. Two regression lines with confidence intervals (shaded areas) were fitted on the data and indicate a quadratic increase of the SRT with advancing age, for both masker types. A significantly steeper slope was found for the SRT in function of age when CT was used as masker compared to SWN (see table 2).

Table 2: Linear Mixed-effect Model: The effect of age and masker on the speech reception threshold. Regression coefficients (β values), standard errors, t-Ratios and p-values are reported per fixed-effect term.

Fixed-effect terms	β value	SE	t-Ratio	p-value
Intercept(for SWN)	-7.55	1.62	-4.67	< 0.001
Age	-0.102	0.0709	-1.44	0.16
Age^2	0.00167	7.74e-04	2.16	0.04
Masker	-14.3	1.05	-13.7	< 0.001
Age:Masker	0.0494	0.0202	2.44	0.02

Envelope tracking and cortical ASSRs to tone pips

In the first section, the statistical analysis regarding the association between speech understanding and envelope tracking is presented using the results obtained during the EEG experiment. Next, the results regarding the effect of age are reported. First of all, we focus on the influence of age on envelope tracking for the fixed, high intelligible SNRs as well as the subject-specific SNRs. Secondly, we asses the SNRs of the ASSRs to tone pips with advancing age to evaluate the effect of age on non-speech stimuli. To assess whether outliers have an influence on the interpretation on our data, we have run all analyses without the data of the participant aged 82 years old. The same conclusions could be drawn from these analyses.

Effect of speech understanding, masker and speech material on neural tracking of the speech envelope

To investigate the association between speech understanding and envelope tracking, the correlation between the actual and reconstructed envelope was predicted using a LMM consisting of four predictors and their interactions (Table 3 and figure 5). First of all, we detected a significant main effect of speech understanding ($p < 0.001$). As shown in figure 5, we obtained a significant increase in envelope tracking with increasing speech understanding. Since we found a significant interaction between speech understanding and the type of speech material or masker (SU:Speech material: $p < 0.001$; SU:Masker: $p = 0.003$; table 3); it seems that the steepness of this increase in envelope tracking depends on the presented speech material and masker. As we did not find a significant three-way interaction, we can infer from the LMM and figure 5 that envelope tracking increases less steeply with speech understanding when CT is used as masker compared to SWN and when the Story is used as target stimulus instead of the Matrix sentences across all ages (Table 3).

In addition, we also found a significant interaction between the type of masker and speech material ($p < 0.001$; table 3). Holm adjusted post-hoc tests indicate a significantly lower envelope tracking for the Story compared to Matrix when CT is used as masker (mean difference between Matrix CT vs Story CT = 0.0423, $p < 0.001$) while the opposite effect is found when SWN is used as masker (mean difference between Matrix SWN vs Story SWN) = -0.011, p = 0.01). Accordingly, we detected a significantly higher envelope tracking for the Matrix when CT was used as masker compared to SWN (mean difference between Matrix SWN vs Matrix CT) = -0.0252, p < 0.001) and a significantly lower envelope tracking for the Story when CT was used compared to SWN (mean difference between Story SWN vs Story CT = 0.0281, p < 0.001).

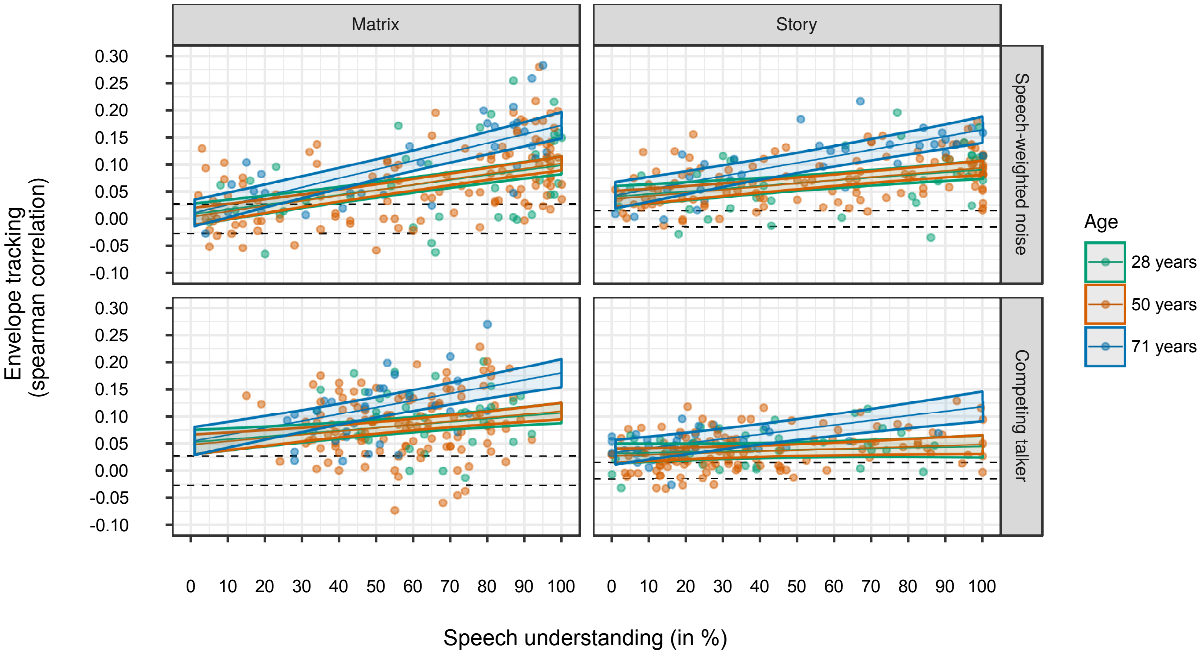

Figure 5: Neural tracking of the envelope in function of speech understanding, measured in 47 normal-hearing adults using two speech materials (Matrix and Story) and two masker types (SWN and CT). Per speech material and masker, three regression lines with confidence intervals (shaded areas) were fitted, representing the predicted data for an example person aged 28 years (young), 50 (middle-aged) or 71 (older) years old (color-coded). The dashed black lines indicate the significance level (95 % confidence interval) of our measure for envelope tracking.

Table 3: Linear Mixed-effect Model: The effect of speech understanding (SU; subject-specific SNRs), speech material, masker and age on envelope tracking. Regression coefficients (β values), standard errors, t-Ratios and p-values are reported per fixed-effect term.

Fixed-effect terms	β value	SE	t-Ratio	p-value
Intercept(for Matrix/SWN)	0.0286	0.0363	0.788	0.43
SU	0.00169	4.22e-04	4	< 0.001
Speech material	0.0326	0.00818	3.99	< 0.001
Masker	0.0446	0.00852	5.24	< 0.001
Age	-0.00104	0.00161	-0.646	0.52
Age^2	1.08e-05	1.76e-05	0.617	0.54
Speech material:Masker	-0.0533	0.00672	-7.93	< 0.001
SU:Age	-4.56e-05	1.91e-05	-2.38	0.02
SU:Age^2	6.30e-07	2.12e-07	2.98	0.003
SU:Speech material	-4.08e-04	1.15e-04	-3.53	< 0.001
SU:Masker	-3.67e-04	1.24e-04	-2.95	0.003

Effect of age

To investigate the neural changes in speech processing with advancing age, we measured neural tracking of the envelope at different understanding levels. First, we will present the results for the two highly intelligible, fixed SNR conditions obtained by fitting a third LMM (Table 4). Next, the outcomes of the LMM reported in table 3 will be described with focus on the effect of age. Lastly, an LFM fitted on the tone pip response data will demonstrate the effect of age on non-speech sounds.

Speech envelope tracking at fixed, highly intelligible SNRs

The LMM, summarized in table 4, showed that envelope tracking significantly increases with age in a quadratic way (p = 0.004). As can be inferred from figure 6, it seems that envelope tracking is stable from 17 until $\pm$ 50 years and then starts to gradually increase with advancing age. In addition, we detected a significant interaction between speech material and age (p = 0.03), indicating a less steeply increase in envelope tracking with age for the Story than the Matrix sentences (Table 4). Lastly, we found significantly lower envelope tracking when the Matrix sentences and the Story were presented at 0 dB SNR compared to the condition without noise (p < 0.001; table 4).

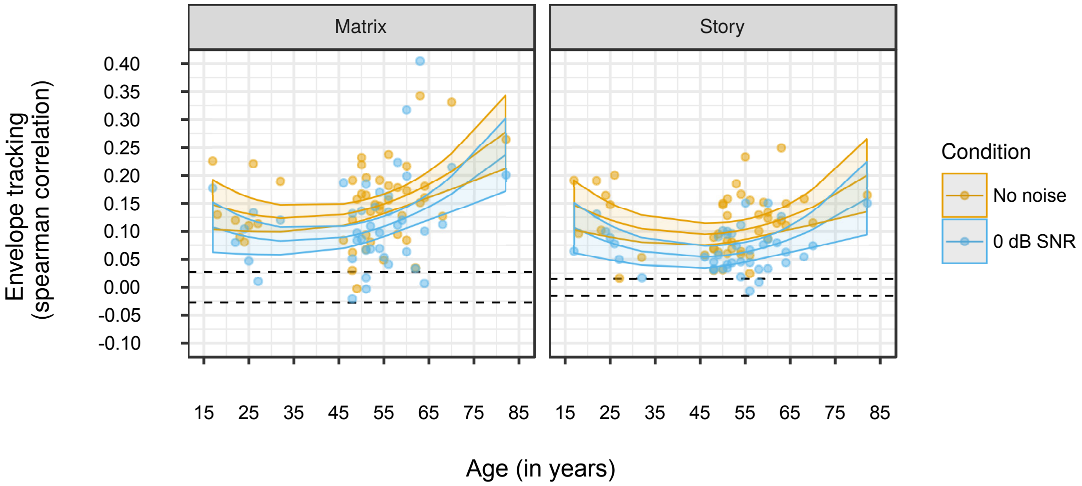

Figure 6: Neural tracking of the envelope in function of age for two fixed SNR conditions (No noise and 0 dB SNR) and two speech materials (Matrix and Story). Per fixed SNR condition (color-coded) and speech material, regression lines with confidence intervals (shaded areas) were fitted, representing envelope tracking in function of age. The dashed black lines indicate the significance level (95 % confidence interval) of our measure for envelope tracking.

Table 4: Linear Mixed-effect Model: The effect of "No noise" versus "0 dB SNR", speech material and age on envelope tracking. Regression coefficients (β values), standard errors, t-Ratios and p-values are reported per fixed-effect term.

Fixed-effect terms	β value	SE	t-Ratio	p-value
Intercept(for Matrix/No noise)	0.215	0.0502	4.28	< 0.001
0 dB SNR	-0.0405	0.00754	-5.37	< 0.001
Speech material	0.0192	0.0276	0.697	0.49
Age	-0.00519	0.00221	-2.35	0.02
Age^2	7.26e-05	2.40e-05	3.02	0.004
Speech material:Age	-0.00118	5.29e-04	-2.24	0.03

Speech envelope tracking at subject-specific SNRs

With regard to the effect of age, we detected a significant interaction between speech understanding and age indicating that the slope for envelope tracking in function of speech understanding becomes quadratically steeper with advancing age (p = 0.003; table 3). The same conclusion can be drawn from figure 5 where three example regression lines are depicted reflecting envelope tracking in function of speech understanding for three ages, 17, 50 and 71 years. The regression lines for the young and middle-aged participant are very similar while the LMM predicts a significantly higher and steeper increase in envelope tracking with speech understanding for an example older NH participant of 71 years.

Cortical responses to non-speech sounds: Tone pips

In addition to continuous speech, we evaluated the effect of age on the responses to non-speech sounds. As depicted in figure 7 and detected by the LFM, we found that the SNR of the tone pip responses significantly decreases with age in a linear way, in contrast to speech envelope tracking (β = -0.0924, SE = 0.0257, p = 0.001). Adding age as a quadratic fixed-effect term in the LFM did not improve the fit. To exclude the possibility that this significant decrease is due to a general decrease in neural activity with advancing age, we also analyzed the effect of age on the total power of the synchronized neural response and EEG noise together (ASSR) and the power of the EEG noise alone. Similarly to evaluating SNR as an outcome measure, we found a significant decrease in total power of the ASSR with advancing age (β = -0.00128, SE = 2.84e-04, p < 0.001) but no significant effect on the power of the EEG noise (β = -2.20e-06, SE = 5.06e-06, p = 0.67).

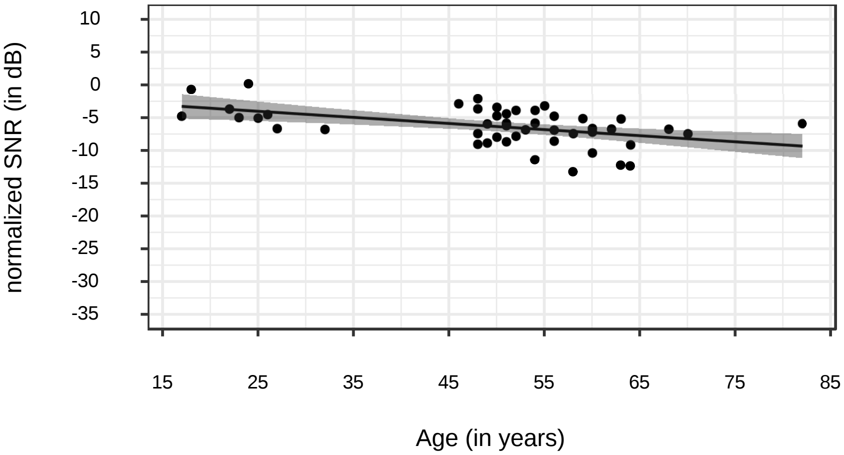

Figure 7: The SNR of the ASSR to a tone pip, with a repetition frequency of 1.92 Hz, in function of age. A regression line with confidence intervals (shaded areas) was fitted representing a linear decrease of the tone pip response with advancing age.

Cognition

In addition to the neural age-related changes in response to frequencies important for speech understanding, it is also known that with advancing age, cognitive functions deteriorate. Moreover, studies have demonstrated a strong association between the decline in cognitive functions such as working memory and inhibition, and increased difficulties with understanding speech in noise. In the next section, we will first describe the relation between age and the results on two cognitive tasks. Secondly, we will assess the specific contribution of working memory (i.e., RST scores) and inhibition (i.e., Stroop scores) on the SRT and on envelope tracking, beyond the effect of age.

Cognition in function of age

As shown in figure 8 and confirmed by the LFM with age as predictor, advancing age resulted in a decrease in cognitive abilities. We found a significant, linear decrease in both the RST scores (β = -0.216, SE = 0.0669, p = 0.002) and Stroop interference scores with advancing age (β = -0.299, SE = 0.0865, p = 0.001). Adding age as a quadratic fixed-effect term to the LFMs did not significantly improve the fit.

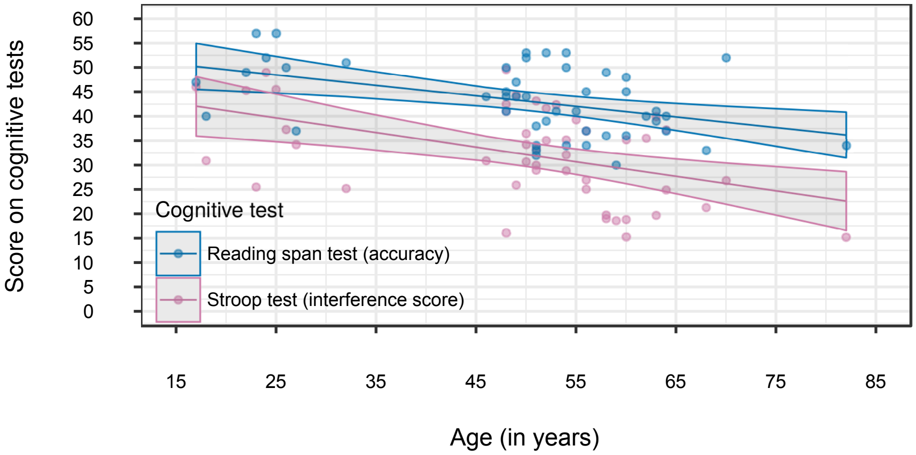

Figure 8: The results on the Reading span test and the Stroop test in function of age. The interference score is calculated as 60 seconds subtracted by the difference score between the incongruent and congruent task. Regression lines with confidence intervals (shaded areas) show a linear decline in cognitive performance with advancing age for both cognitive tests (color-coded).

How does cognition relate to the effect of age on the SRT and envelope tracking?

Speech understanding in noise

To better understand the interplay between cognition, age and speech understanding in noise, we used likelihood ratio tests and the AIC to evaluate if adding the Stroop or RST scores to the LMM reported in table 2, improved the model's fit. Adding the Stroop as a main, fixed-effect term to the model did not significantly improve the model's fit ($p > 0.05$). This means that it is unlikely that the Stroop results explain a part of the inter-subject variability of the SRTs (improvement in R^2 = 5.18e-04 %). Adding the RST scores as a main, fixed-effect term, however, did improve the model's fit ($p < 0.05$). In other words, the score on the RST explains part of the inter-subject variability of the SRT, beyond age (improvement in R^2 = 0.49 %). The LMM indicated that a higher, poorer SRT was obtained for participant with a lower, worse score on the RST (β = -0.0688, SE = 0.0299, p = 0.03). As the interaction between age or type of masker and the RST scores did not further improve the model, we can assume that the differential effect of age for the two maskers depends on other factors than working memory.

Envelope tracking

Lastly, we looked into the relation between envelope tracking and the scores on the cognitive tasks by adding the Stroop and RST scores as fixed-effect terms to the best fitted model described in table 3. Although adding the Stroop or RST scores as main fixed-effect terms did not improve the model's fit ($p > 0.05$), likelihood ratio tests and the AIC showed an improvement when adding the interaction between the Stroop scores and the type of speech material ("Stroop:Speech material") or the interaction between the RST scores and the type of masker ("RST:Masker"). More specifically, the significant interaction between the Stroop scores and speech material indicated that enhanced envelope tracking is associated with lower, worse scores on the Stroop test, but only when the Story was the target talker (β = 0.00102, SE = 3.32e-04, p = 0.002). A similar effect was found for the RST scores when CT was used as masker, i.e., lower, worse scores on the RST were associated with an enhanced envelope tracking (β = 0.00128, SE = 4.35e-04, p = 0.003).

Discussion

The results of the present study demonstrate that age affects speech understanding in noise as well as neural tracking of the envelope in a quadratic way. More specifically, we found that speech understanding worsens with advancing age and that this effect is more detrimental when speech is embedded in a competing talker. Furthermore, we found that envelope tracking increases with speech understanding but that this depends on the age of the participant as well as the type of speech material and masker that was presented. In contrast to this, the cortical responses to the tone pips decreased linearly with advancing age.

Age affects speech understanding in noise in a quadratic way

Our results are in line with previous studies showing that the SRT worsens with advancing age, despite having audiometric thresholds within the normal range (Goossens et al., 2017; Helfer and Freyman, 2014; Füllgrabe et al., 2015). Similarly to the review of Moore et al. (2014), our results also demonstrate a supra-linear increase in the SRT with advancing age. In line with our hypothesis and the literature (Desjardins and Doherty, 2013; Festen and Plomp, 1990; Goossens et al., 2017; Helfer and Freyman, 2014), we found that the quadratic increase in SRT with age was substantially less steep for SWN, indicating a more detrimental effect of age when speech is presented with a CT. In view of this, the substantially smaller difference in SRT between young and older adults for SWN could explain why several studies found small, non-significant differences between young versus middle-aged or older NH participants for an energetic masker (Helfer and Vargo, 2009; Schoof and Rosen, 2014). In addition, the quadratic effect of age also shows the importance of the choice of age range. For instance, the difference in SRT will be substantially larger when comparing a group of young with older NH adults when the ages of the older group range from 60 to 70 instead of 50 to 60 years. Taken together, our data shows that age should be used as a continuous variable in future studies to gain more detailed insight into the effect of age on speech understanding in noise.

The more detrimental age effect for CT could be due to age-related temporal deficits or a decline in cognition with advancing age (CHABA, 1988; Humes et al., 2012; Pichora-Fuller et al., 2016). We assessed the specific contribution of these factors by relating the results on two cognitive tasks with speech understanding in noise. We found that the lower scores on the RST, i.e., working memory, were significantly associated with worse SRTs while no association was found between the Stroop scores and SRT. Since the association between RST and SRT yields for both masker types, our results suggest that temporal processing deficits rather than cognitive decline, may underlie the more detrimental age effect for CT. This is plausible as previous studies also found evidence for the decreased benefit of listening in the gaps with advancing age (Desjardins and Doherty, 2013; Festen and Plomp, 1990; Goossens et al., 2017; Helfer and Freyman, 2014). Nevertheless, the contribution of cognition cannot entirely be excluded because of for instance the possible lack of sensitivity of the cognitive measures used in this study. More specifically, the inhibitory processes activated for the Stroop test may be only visual orientated in contrast to the auditory speech-in-noise task. This could be a problem as the age-related decline of inhibitory processes is likely to be modality dependent (Guerreiro et al., 2010). Another possibility is the strict inclusion criteria used in the present study. Our participants are representing the best performers of a NH population across the adult lifespan which could lead to non-significant effects.

Neural tracking of the speech envelope and modulations of non-speech sounds across the adult lifespan

Envelope tracking increases in a quadratic way with advancing age

To our knowledge, this is the first study investigating the effect of age on neural tracking of envelope of running speech across the adult lifespan, i.e., including young and older but also middle-aged NH adults. Our results are in agreement with a part of the literature that demonstrates an increase in envelope tracking with advancing age (non-speech sounds: Goossens et al., 2016; Bidelman et al., 2014; Sörös et al., 2009; Rufener et al., 2016; Tlumak et al., 2015; running speech: Presacco et al., 2016b; Presacco et al., 2016a). It should be pointed out, however, that we found a quadratic relation between envelope tracking and age which has, up to our knowledge, not been demonstrated before. Moreover, a similar envelope tracking for a young (28 years) and middle-aged (51 years) NH adult was found whereas envelope tracking of an example older NH person (71 years) was substantially enhanced (figure 5). Thus, in line with the studies including middle-aged participants (Goossens et al., 2016; Tlumak et al., 2015), our results suggest that aging results in a gradual enhancement in envelope tracking, most apparent at an older age. Our data corroborates with the findings of previous research that future studies should include middle-aged participants to determine the precise starting point of enhanced envelope tracking with aging.

Envelope tracking increases more with speech understanding for older than young and middle-aged adults

In line with the results for young adults (Ding and Simon, 2012; Vanthornhout et al., 2018), we found an increase in envelope tracking with increasing speech understanding for middle-aged and older NH adults. In addition, our results also demonstrated that envelope tracking for older adults increases more with increasing speech understanding than younger and middle-aged NH adults. In other words, it seems that the effect of age is more apparent when participants are better in understanding the target talker than when it is very difficult to understand speech, e.g., at 20% SU.

As we found enhanced envelope tracking for similar speech understanding levels, higher envelope tracking between individuals seems to not result from better speech understanding but is rather associated with the degree of difficulty that persons experience when processing speech. Goossens et al. (2018) investigated the relation between speech understanding and cortical encoding of the envelope across the lifespan and found that enhanced cortical envelope encoding is related to poorer speech understanding for NH adults. Although enhanced envelope tracking is likely to reflect the speech-in-noise difficulties in older adults, it is still unknown which factors contribute to this enhancement.

A first possible explanation includes the temporal deficits that adults develop with advancing age. In other words, to compensate for the speech-in-noise difficulties, older NH adults rely more on the low modulation frequencies important for speech understanding, i.e., the envelope, resulting in an enhanced envelope tracking. To date, there is evidence for this hypothesis for hearing impaired persons as studies have shown an increased sensitivity for envelope modulations in persons with sensorineural hearing loss (Wallaert et al., 2017; Millman et al., 2017). However, to our knowledge no study has found a decreased speech understanding in noise in NH older adults that was associated to increased envelope sensitivity. Secondly, it is also shown that with advancing age, the connection between brain regions deteriorates and the activity in regions outside the core speech processing network increases (Peelle et al., 2010; Wong et al., 2009; Davis et al., 2008; Cabeza, 2002). Hence, decreased connectivity in older adults would result in activating more brain regions to process speech in the same way compared to their younger counterparts.

A similar explanation can be inferred from a cognitive perspective, where enhanced envelope tracking could reflect the inefficient use of cognitive resources (Presacco et al., 2016a) or the increased effort that older adults experience (e.g. Degeest et al., 2015; Lemke and Besser, 2016; Anderson Gosselin and Gagné, 2011). In the present study, we related envelope tracking with the results on two cognitive tasks. In line with the results of Presacco et al. (2016a), we found that enhanced envelope tracking was associated with lower scores on the Stroop test, when the Story was presented. The fact that we only found this for the Story, might be explained by the higher amount of semantic context present in the Story than Matrix (Verschueren et al., submitted). However, enhanced envelope tracking was also associated with a lower RST score, when CT was used as masker. As the RST assesses working memory, we did not expect this effect to be only present for CT. It could be that certain effects may not be revealed because of the strict inclusion criteria used in this study.

In spite of this possible reason, the less apparent effect of age at lower understanding levels (e.g., 20% SU) supports the role of cognition or effort in enhanced envelope tracking. When it is too difficult to understand the target talker, participants are not motivated anymore and are likely to give up (Wu et al., 2016; Pichora-Fuller et al., 2016). As a result of this, a minimal amount of brain regions similar to younger adults will be active to process the stimulus. In contrast, at a higher level of speech understanding (e.g., 50 or 60% SU) older adults are more motivated and will spend more effort which could result in a higher envelope tracking. Although this is plausible, we have to note that it is also possible that the subject-specific SNR reflecting 20% SU, was too low to reconstruct the envelope from the EEG.

A differential effect of age for running speech versus tone pips

In contrast to the enhanced envelope tracking for running speech, we found a linear decrease in cortical ASSRs with advancing age. This is in line with the study of Henry et al. (2017) who found weaker entrainment to frequency-modulated stimuli in older versus young NH adults. Conversely, studies also showed increases in cortical ASSRs to non-speech sounds (Goossens et al., 2016; Tlumak et al., 2015). Altogether, it is not likely that the differential age effect on envelope tracking versus ASSRs to tone pips can be fully attributed to the difference between speech versus non-speech sounds. Another, more likely, reason could involve the repetition frequency of the presented stimulus. The study of Tlumak et al. (2015) supports this explanation as their results suggest a turning point around 2.5 Hz from larger ASSRs in young compared to middle-aged and older adults to smaller ASSRs for higher modulation frequencies. To confirm this hypothesis, it would be interesting to include multiple modulation frequencies when evaluating the effect of age on non-speech sounds at a particular modulation frequency.

Envelope tracking depends on the type of masker and speech material

Lastly, with regard to the effect of speech material and masker, our results showed higher envelope tracking for Story compared to Matrix in SWN and the opposite for CT. We did not expect these results as we carefully matched most of the acoustical parameters of the target talkers (sex, root mean square level and spectrum). However, other factors such as modulation frequencies, attention or other top-down processes could underlie these results.

First of all, recalling the Matrix sentences out loud could make the participants more engaged in the task compared to passively listening to the Story. This is a plausible hypothesis as different studies have demonstrated the enhanced effect of attention on envelope tracking (Ding and Simon, 2012; O'Sullivan et al., 2015; Das et al., 2016). However, this does not explain why we only saw this effect for SWN and not for CT. Another reason regards the higher amount of semantic context present in the Story and therefore resulting in an enhanced neural envelope tracking (Verschueren et al. submitted).

A possible explanation for only finding enhanced envelope tracking for the Story in SWN, is based on the use of subject-specific SNRs. Whereas the SNRs of the Matrix sentences were determined based on the outcomes of a behavioral test, the SRTs for the Story were based on ratings and then adjusted (see figure 1). Furthermore, when looking in retrospect to the data, we mainly found small correlations around the significance level when the Story was presented in CT. This may be associated to the large number of low speech understanding scores obtained for this condition. Hence, it might be necessary in future studies to adjust the speech understanding levels for the Story in CT and to also validate the self-assessed Békesy procedure for older adults.

Future work

Using a more ecologically valid measure than ABRs or ASSRs, we demonstrated a quadratic increase in neural envelope tracking with advancing age which can be associated to the decreased speech understanding in noise in older NH adults. Hence, envelope tracking may have the potential to complement current behavioral speech-in-noise tests in the clinic. However, more studies are needed to understand the underlying reasons and neural mechanisms behind this enhanced envelope tracking. First of all, it would be interesting to also administer cognitive tasks specific for the auditory modality. Secondly, including listening effort measures such as ratings, EEG-based measures or dual-task paradigms could be valuable to unravel the different reasons (review see Pichora-Fuller et al., 2016; McGarrigle et al., 2014). Last, conducting neural source analysis or using fMRI could also contribute in the search for the underlying mechanisms.

Conclusion

The present study provides new insights into the changes in envelope tracking when we grow older. Envelope tracking increases gradually with advancing age, while the tone pip responses linearly decrease. In addition, we find an association between speech understanding and envelope tracking, with a stronger association for older adults. Taking the cognitive tests results into account, enhanced envelope tracking may be the result of a higher activation of different brain regions when older adults process speech. Hence, this could reflect the inefficient use of cognitive resources or increased listening effort, often observed in behavioral research. The relation between speech understanding and envelope tracking across the lifespan supports the use of envelope tracking measures in clinical tests, such as an objective test of speech understanding (Vanthornhout et al., 2018).

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Disclosures

The authors declare that there are no conflicts of interest.

Author Contributions

L.D, J.V., T.F conceived and designed the research; L.D performed experiments; L.D. analyzed data; L.D, J.V., T.F interpreted results of experiments; L.D. prepared figures; L.D, J.V., T.F drafted manuscript

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