Differences in speech processing among elderly hearing-impaired listeners with or without hearing aid experience: Eye-tracking and fMRI measurements

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In contrast to the effects of hearing loss, the effects of hearing aid (HA) experience on speech-in-noise (SIN) processing are underexplored. Using an eye-tracking paradigm that allows determining how fast a participant can grasp the meaning of a sentence presented in noise together with two pictures that correctly or incorrectly depict the sentence meaning (the 'processing time'), Habicht *et al.* (2016, 2017) found that inexperienced HA (iHA) users were slower than experienced HA (eHA) users, despite no differences in speech recognition. To examine the influence of HA use on SIN processing further, the eye-tracking paradigm was adapted for functional magnetic resonance imaging (fMRI) measurements. Groups of eHA ($N = 13$) and iHA ($N = 14$) users matched in terms of age, hearing loss and working memory capacity participated. As before, despite no difference in speech recognition, the iHA group had longer processing times than the eHA group. Furthermore, the iHA group showed more brain activation for SIN relative to noise-only stimuli in left precentral gyrus, cerebellum anterior lobe, superior temporal gyrus and right medial frontal gyrus compared to the eHA group. Together, these results support the idea that HA experience positively influences the ability to process SIN quickly and that it reduces the recruitment of brain regions outside the core speech-comprehension network.

INTRODUCTION

To investigate the effects of cognitive-linguistic processes on speech-in-noise (SIN) processing, Wendt *et al*. (2014) developed an eye-tracking paradigm for estimating *how quickly* a participant can grasp the *meaning* of an acoustic sentence-in-noise stimulus presented concurrently with two similar pictures, only one of which depicts the sentence meaning correctly (the 'processing time'). Previously, Habicht *et al.* (2016, 2017) found that hearing-impaired (HI) listeners with HA experience had shorter processing times than HI listeners without HA experience, despite no differences in speech recognition performance or behavioral reaction times (i.e.,

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button presses). Based on a literature review, Peelle and Wingfield (2016) concluded that, to compensate for their hearing deficits, HI listeners recruit regions outside the core speech-processing network (comprising middle temporal and inferior frontal gyrus) in order to achieve speech comprehension. Up until now, however, it remains unclear how interventions for hearing impairment (e.g., hearing devices) affect the neuronal processes underlying SIN processing.

The current study aimed to shed some light on how HA use may affect SIN processing abilities by investigating HA experience-related effects on brain activation. To confirm the previously observed difference in sentence processing times, we first made eye-tracking measurements with groups of experienced and inexperienced HA users. To explore differences in brain activation during speech comprehension among the two participant groups, we then performed functional magnetic resonance imaging (fMRI) measurements. For that purpose, we adapted the eye-tracking paradigm for measuring blood oxygenation level-dependent (BOLD) responses. Based on related literature findings, our hypotheses were as follows:

1. The iHA group will have longer processing times than the eHA group.
2. The iHA group will show more brain activation in areas outside the core speech-comprehension network compared to the eHA group.

METHODS

Participants

Thirteen habitual HA users with at least one year of bilateral HA experience (eHA group) and 14 inexperienced HA users with no previous HA experience (iHA group) were recruited. Inclusion criteria were (1) age from 60 to 80 yr, (2) bilateral, sloping, sensorineural hearing loss in the range from 40 to 80 dB HL between 3 and 8 kHz, (3) self-reported normal or corrected-to-normal vision, and (4) no conditions that were contraindicative for fMRI measurements (e.g., a pacemaker). The two groups were matched closely in terms of age, pure-tone average hearing loss calculated across 0.5, 1, 2 and 4 kHz and left and right ears (PTA), working memory capacity as measured using a reading span test (Carroll *et al.*, 2015) and 80%-correct speech reception threshold (SRT_{80}) performance (see Table 1).

	eHA	**iHA**
N	13	14
Age (yr)	68.8 (4.0)	68.8 (5.9)
PTA (dB HL)	33.9 (7.4)	31.1 (7.1)
RS (%-correct)	43.0 (11.7)	38.9 (14.2)
SRT_{80} (dB SNR)	−1.6 (1.0)	−1.7 (1.0)

Table 1: Means (and standard deviations) for age, PTA, reading span (RS), and SRT_{80} for the two groups of participants.

Speech-in-noise (SIN) stimuli

For the acoustic stimuli, two sentence structures of the “Oldenburg corpus of Linguistically and Audiologically Controlled Sentences” (OLACS; Uslar *et al*., 2013) were used: (1) subject-verb-object sentences with a canonical word order and therefore ‘low’ linguistic complexity, and (2) object-verb-subject sentences with a non-canonical word order and therefore ‘high’ linguistic complexity (Table 2). In each sentence, there are two characters (e.g., a dragon and a panda), one of which (the subject) performs a given action with the other (the object). In the German language, the linguistic complexity of these sentences is determined by relatively subtle grammatical or acoustic cues, e.g., “Der müde Drache fesselt den großen Panda” (meaning: “The tired dragon ties up the big panda”; low complexity) vs. “Den müden Drachen fesselt der große Panda” (meaning: “The big panda ties up the tired dragon”; high complexity). The stimuli were presented via earphones at the individual SRT_{80}. For the masker, stationary speech-shaped noise calibrated to a nominal sound pressure level of 65 dB was used. To ensure audibility, linear amplification in accordance with the “National Acoustic Laboratories-Revised” (NAL-R) prescription formula (Byrne *et al*., 2001) was applied using the Master Hearing Aid research platform (Grimm *et al*., 2006).

Low	De*r*$_{nom}$	müd*e*$_{nom}$	Drach*e*	fesselt	de*n*$_{acc}$	groß*en*$_{acc}$	Panda.
	Meaning: “The dragon ties up the panda.”						
High	De*n*$_{acc}$	müd*en*$_{acc}$	Drach*en*	fesselt	de*r*$_{nom}$	groß*e*$_{nom}$	Panda.
	Meaning: “The panda ties up the dragon.”						

Table 2: Examples of sentences from the “Oldenburg corpus of Linguistically and Audiologically Controlled Sentences” (Uslar *et al*., 2013) with two levels of linguistic complexity (low, high). In each case, the grammatically salient *word endings* and corresponding cases (nom = nominative; acc = accusative) are indicated, as are the English meanings.

Eye-tracking measurements

The sentence-in-noise stimuli were presented together with two similar pictures displayed on a monitor in front of the participants. The task of the participant was to identify the picture that matched the acoustic stimulus by pressing a button as fast as possible after the acoustic presentation. During the stimulus presentation, the eye movements of the participant were recorded. If a participant has understood the meaning of a sentence, (s)he will automatically start fixating the corresponding picture. In the following, the time elapsed for this to occur will be referred to as the processing time.

A total of four blocks were performed per participant. Within a block there were 30 trials based on 15 sentences with low linguistic complexity and 15 sentences with high linguistic complexity, plus seven catch trials (see Habicht et al., 2016). The different blocks were presented in randomized order across the different participants.

fMRI measurements

For the fMRI measurements, the eye-tracking paradigm was adapted. The task of the participants was to identify the target picture by pressing a button on a button pad after the presentation of the acoustic stimulus. SIN stimuli with the two levels of linguistic complexity (SIN_{low}, SIN_{high}) were presented together with the corresponding picture sets. In addition, a noise-only condition was included as baseline. In that case, only one picture of a given picture set was displayed, and the task of the participant was to identify the location of the picture (left or right) by pressing a corresponding button on the button pad.

Using this approach, BOLD responses were measured for each participant and stimulus condition (SIN_{low}, SIN_{high}, noise-only). Using the BOLD responses, different contrasts were made to investigate the main effects of stimulus type and linguistic complexity across all participants. The main effect of stimulus type was assessed by contrasting all SIN trials (SIN_{low}, SIN_{high}) with all noise trials (SIN > noise). Based on previous studies, it was expected that the SIN stimuli would lead to more activation in frontotemporal areas including bilateral temporal cortex and left inferior frontal gyrus compared to noise-only stimuli (Adank, 2012; Lee *et al.*, 2016; Rodd *et al.*, 2005). The main effect of linguistic complexity was assessed by contrasting the SIN_{high} and SIN_{low} trials (SIN_{high} > SIN_{low}). It was expected that high-complexity sentences would lead to more activation in frontal lobe (including left inferior frontal gyrus and middle frontal gyrus) compared to low-complexity sentences (e.g., Friederici *et al.*, 2006; Lee *et al.*, 2016; Peelle *et al.*, 2009; Rodd *et al.*, 2005). Additionally, the interaction between participant group and stimulus type was assessed by contrasting the SIN > noise contrast of the iHA group with the SIN > noise contrast of the eHA group (iHA > eHA for SIN > noise). It was expected that to achieve speech comprehension the iHA group would show more brain activation for the contrast SIN > noise in frontotemporal areas in comparison to the eHA group (Peelle and Wingfield *et al.*, 2016; Sandmann *et al.*, 2015). Furthermore, the interaction between participant group and linguistic complexity was assessed by contrasting the SIN_{high} > SIN_{low} contrast of the iHA group with the SIN_{high} > SIN_{low} contrast of the eHA group (iHA > eHA for SIN_{high} > SIN_{low}). Based on previous eye-tracking results (Habicht *et al.*, 2016; 2017), it was expected that no group differences would be apparent.

The fMRI data were recorded in one block of 150 trials. Specifically, there were 50 trials per stimulus condition (SIN_{low}, SIN_{high}, noise only). The trials from the three conditions were presented in randomized order. After the 150 trials, a structural image was acquired that served as an anatomical reference.

Test protocol

All participants attended three visits. At the first visit, the SRT_{80} measurements were performed. In addition, event-related potential measurements were carried out for another study. At the second visit, the eye-tracking measurements took place. At the third visit, the fMRI measurements were carried out. The first and second visit took 2 h each, while the third visit took 1 h.

RESULTS

Eye-tracking measurements

On average, the eHA and iHA groups achieved 91.0%-correct (standard deviation: 0.07%-correct) and 89.5%-correct (standard deviation: 0.08%-correct) picture recognition rates. An independent *t*- test revealed no significant difference in terms of picture recognition rates between the two groups ($t_{25} = -0.5$, $p > 0.05$).

On average, the eHA and iHA groups had longer (poorer) processing times for the sentences with high linguistic complexity (means: 1182 and 1679 ms; standard deviations: 536 and 645 ms) than for the sentences with low linguistic complexity (means: 846 and 1132 ms; standard deviations: 211 and 480 ms). Furthermore, the iHA group had longer processing times than the eHA group (means: 1406 and 1014 ms; standard deviations: 624 and 435 ms). To analyze these data further, we performed an analysis of variance with listener group as between-subject factor and linguistic complexity (low, high) as within-subject factor. Significant effects of listener group [$F(1,25) = 5.5$, $p < 0.026$, $\eta_p^2 = 0.18$] and linguistic complexity [$F(1,25) = 21.0$, $p < 0.0001$, $\eta_p^2 = 0.46$] were found, but no interaction ($p > 0.05$).

fMRI measurements

On average, the eHA and iHA groups achieved 88.5%-correct (standard deviation: 10.4%-correct) and 84.1%-correct (standard deviation: 4.4%-correct) picture recognition rates. An independent *t*-test revealed no significant difference in terms of picture recognition rates between the two groups ($t_{25} = -1.4$, $p > 0.05$).

Concerning the effect of stimulus type, the SIN stimuli led to more activation along bilateral superior temporal gyrus, frontal lobe (including left superior frontal gyrus, left inferior frontal gyrus, right middle frontal gyrus and left precentral gyrus) and bilateral middle occipital gyrus compared to the noise-only stimuli ($T = 6.27$, $p < 0.05$, family-wise-error (FWE) corrected). Figure 1A shows brain regions with increased activation from the SIN > noise contrast analysis.

Concerning the effect of linguistic complexity, the SIN_{high} stimuli led to more activation in bilateral frontal gyrus (including inferior and middle frontal gyrus), left precuneus, right middle occipital gyrus and left temporal lobe (including middle temporal gyrus and superior temporal gyrus) compared to the SIN_{low} stimuli ($T = 3.43$, $p < 0.001$, uncorrected). Figure 1B shows brain regions with increased activation from the $SIN_{high} > SIN_{low}$ contrast analysis.

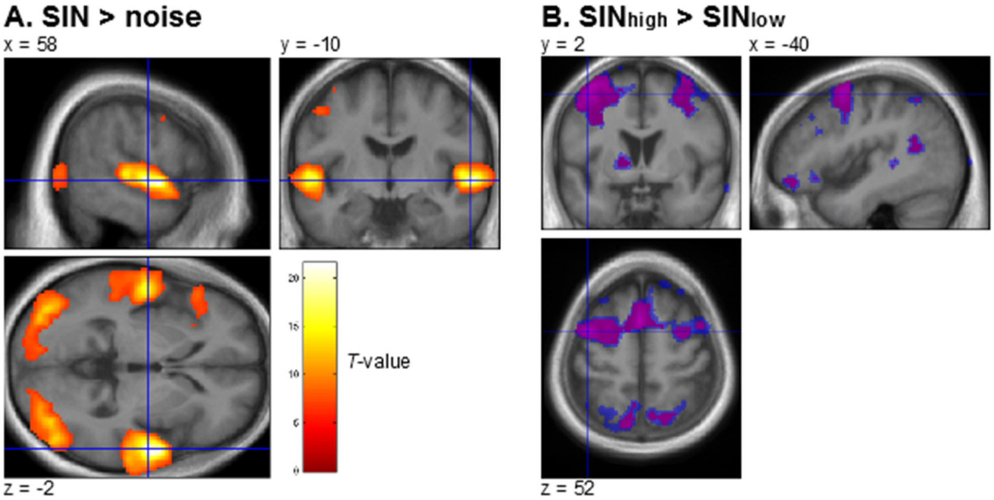

Fig. 1: Sagittal (X), coronal (Y) and axial (Z) views at the location of the global *t*-value maxima (blue crosses). A: Main effect of stimulus type for BOLD contrast SIN > noise at (FWE-corrected $p < 0.05$). B: Main effect of linguistic complexity for BOLD contrast $SIN_{high} > SIN_{low}$ at (uncorrected $p < 0.001$ in purple and uncorrected $p < 0.005$ in blue).

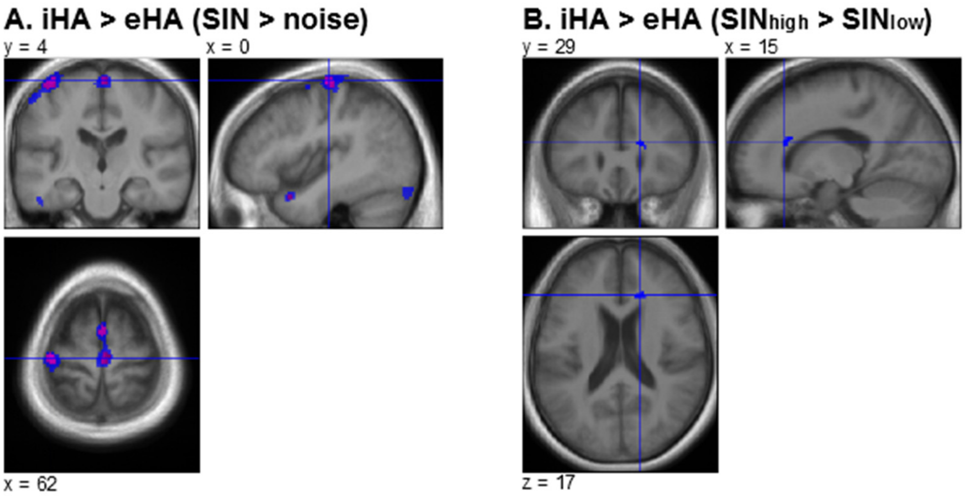

Fig. 2: Sagittal (X), coronal (Y) and axial (Z) views at the location of the global *t*-value maxima (blue crosses). A: Interaction of listener group × stimulus type for BOLD contrast iHA > eHA and SIN > noise (uncorrected $p < 0.001$ in purple and uncorrected $p < 0.005$ in blue). B: Interaction of listener group × ling. complexity for BOLD contrast iHA > eHA and $SIN_{high} > SIN_{low}$ at (uncorrected $p < 0.001$ in purple and uncorrected $p < 0.005$ in blue).

Concerning the interaction between listener group and stimulus type, the iHA group showed more activation for the SIN > noise contrast in left precentral gyrus, left cerebellum anterior lobe, right medial frontal gyrus, and left superior temporal gyrus compared to the eHA group ($T = 3.5$, $p < 0.001$, uncorrected). Figure 2A shows brain regions with increased activation from the iHA > eHA (SIN > noise) contrast analysis.

Concerning the interaction between listener group and linguistic complexity, no significant contrasts were observed. Figure 2B shows images from the iHA > eHA ($SIN_{high} > SIN_{low}$) contrast analysis.

SUMMARY AND CONCLUSIONS

In the current study, a cross-sectional design was used to investigate the influence of HA experience on cognitive processes related to sentence comprehension in noise. Using the eye-tracking paradigm of Wendt *et al.* (2014), sentence-in-noise processing times were measured. Additionally, fMRI measurements were performed to measure brain activation patterns in response to SIN and noise-only stimuli. All SIN stimuli were presented at the individual SRT_{80} with individual NAL-R amplification to ensure audibility. The iHA participants had significantly longer processing times than participants matched in terms of age, PTA, working memory capacity and SRT_{80} with at least one year of bilateral HA experience. This is consistent with earlier findings and suggests poorer SIN processing due to untreated hearing loss. Regarding the fMRI measurements, sentences with high linguistic complexity activated additional brain areas in left frontal regions compared to sentences with low linguistic complexity, consistent with the literature. Furthermore, compared to the eHA group the iHA group showed more activation for SIN relative to noise-only stimuli in left precentral gyrus, left cerebellum anterior lobe, right medial frontal gyrus, and left superior temporal gyrus. This suggests that iHA users rely on additional cortical processing to compensate for their hearing deficits to achieve speech comprehension. Altogether, the current study thus confirms that HA experience leads to faster sentence-in-noise processing and also indicates that it reduces the recruitment of brain regions outside the core sentence-comprehension network.

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