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Effect of Audibility and Suprathreshold Deficits on Speech Recognition for Listeners With Unilateral Hearing Loss

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Objectives: We examined the influence of impaired processing (audibility and suprathreshold processes) on speech recognition in cases of sensorineural hearing loss. The influence of differences in central, or top-down, processing was reduced by comparing the performance of both ears in participants with a unilateral hearing loss (UHL). We examined the influence of reduced audibility and suprathreshold deficits on speech recognition in quiet and in noise.

Design: We measured speech recognition in quiet and stationary speech-shaped noise with consonant–vowel–consonant words and digital triplets in groups of adults with UHL (n = 19), normal hearing (n = 15), and bilateral hearing loss (n = 9). By comparing the scores of the unaffected ear (UHL+) and the affected ear (UHL−) in the UHL group, we were able to isolate the influence of peripheral hearing loss from individual top-down factors such as cognition, linguistic skills, age, and sex.

Results: Audibility is a very strong predictor for speech recognition in quiet. Audibility has a less pronounced influence on speech recognition in noise. We found that, for the current sample of listeners, more speech information is required for UHL− than for UHL+ to achieve the same performance. For digit triplets at 80 dBA, the speech recognition threshold in noise (SRT) for UHL− is on average 5.2 dB signal to noise ratio (SNR) poorer than UHL+. Analysis using the speech intelligibility index (SII) indicates that on average 2.1 dB SNR of this decrease can be attributed to suprathreshold deficits and 3.1 dB SNR to audibility. Furthermore, scores for speech recognition in quiet and in noise for UHL+ are comparable to those of normal-hearing listeners.

Conclusions: Our data showed that suprathreshold deficits in addition to audibility play a considerable role in speech recognition in noise even at intensities well above hearing threshold.

Key words: Audibility, Audiology, Bottom-up processing, CVC words, Digits in noise, Hearing impairment, Hearing loss, Speech in noise, Speech intelligibility index, Speech recognition, Supra-threshold deficits, Top-down processing, Unilateral hearing loss.

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INTRODUCTION

Many studies have shown that hearing impairment can have a serious impact on quality of life (Herbst & Humphrey 1980; Bess et al. 1989; Hallberg & Carlsson 1991; Kramer et al. 2002). In many different daily situations, listeners with hearing impairment have to exert themselves, and sometimes fail to understand spoken messages. The ability to understand speech varies among hearing-impaired persons, even when their pure-tone audiograms are similar (Bosman & Smoorenburg. 1995), in particular in conditions where background noise is involved (Festen & Plomp. 1990; Houtgast & Festen 2008).

The process of speech understanding can be divided roughly into two interacting processes: the first process deals with signal processing, that is, how the sound is captured and processed by the auditory system (referred to as bottom-up processing). The second process deals with sorting the information to come to a meaningful message (referred to as top-down processing). See, for example, Bronkhorst (2015) for a review on the processing of speech and the mechanisms that play a role. The aim of the current study is to explore the specific effects of peripheral hearing loss (bottom-up processing) on speech recognition and to identify to what extent suprathreshold deficits play a role.

Sensorineural hearing loss results in impaired bottom-up processing first of all due to decreased audibility. Second, the capacity to process the audible speech information is impaired, which is generally referred to as a suprathreshold deficit. In the literature, many studies have been carried out to try to quantify these deficits and to differentiate between them (Plomp 1978; Zwicker & Schorn 1982; Glasberg et al. 1987; Dreschler & Leeuw 1990; Moore 1996; George et al. 2006; Stenfelt 2008). Both reduced audibility and impaired suprathreshold processing originate from physiological defects somewhere along the auditory pathway, and result in elevated auditory thresholds and phenomena like recruitment, spectro-temporal smearing, or decreased localization (Plomp & Mimpen 1979; Glasberg et al. 1987; Festen & Plomp 1990; Moore & Glasberg 1993; Robles & Ruggero 2001; George et al. 2006; Goverts & Houtgast 2010; Ruggles et al. 2011). Poorer speech recognition in quiet is thought to be largely due to decreased audibility. Ching et al. (2011) have shown that, after accounting for hearing loss, decreased frequency resolution or the presence of dead regions have no significant effect on speech recognition. However, Ching and Dillon (2013) have shown that the ability to extract target speech information from an audible signal that comprises speech and masker decreases with increasing hearing loss. These effects may be different for several subgroups of listeners with impaired hearing and for specific aspects of speech recognition (van Schijndel et al. 2001; Stenfelt 2008; Goverts & Houtgast 2010).

Top-down processing plays an important role when the available speech information has to be transformed into a meaningful message. It primarily involves nonauditory factors such as cognitive and linguistic skills and notably comes to play in more

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challenging listening situations, such as with speech in background noise. These skills are utilized in the formation of the auditory event, for example, the perception of a word/sentence, based on the processed stimulus. Variance in these top-down factors results in differences in speech understanding among listeners with comparable auditory (i.e., bottom-up) functioning. Many studies show that there is a significant correlation between speech intelligibility in noise and cognitive function (Arlinger 2003; Alain & Tremblay 2007; Pichora-Fuller 2007; Ching & Dillon 2013; Humes et al. 2013). Relevant cognitive capacities include working memory capacity and phonological skills (see Rudner & Lunner 2014, for a narrative overview). Besser (Reference Note 1) and Humes et al. (2013) have shown that cognitive variables like working memory, semantic closure, and verbal speed of processing influence speech understanding. Linguistic abilities are a specific category of cognitive skills and, for example, Kaandorp et al. (2016) have found that lexical-access ability is a strong predictor of speech recognition in normal hearing (NH) listeners.

It is not possible to consider top-down and bottom-up processing as two entirely independent processes. Both influence the outcome of psychophysical tests like speech recognition measurements or subjective assessments. There is no clear proof that late-onset hearing loss reduces cognitive functions, but indirect evidence supports this hypothesis. A recent review by Lesicko and Llano (2017) showed that loss of (bottom-up) sensory input results in a variety of changes in descending projections. There might be some rebalancing between bottom-up and top-down processing, but underlying mechanisms are not yet understood. Nevertheless, it is possible to disentangle bottom-up and top-down processing to some extent. George et al. (2007) have found that the speech recognition threshold (SRT) in stationary noise was mainly related to audiometric hearing loss and not to nonauditory factors. But the SRT in modulated noise appeared to be related to nonauditory factors. Besser et al. (2015) showed that auditory and cognitive interactions were reflected by the combined influence on spatialized speech recognition, but also that predictors were different for younger and older listeners.

Both from a scientific and from a clinical perspective, it is relevant to be able to discern the aspects that play a role in speech recognition. Enhanced insight in the processes that play a role might enable more patient-targeted rehabilitation. Hearing aids are now mainly programmed based on hearing threshold without taking into account differences in suprathreshold processing, cognition, or linguistic abilities across subjects. More insight into the relative contribution of bottom-up and top-down processes can lead to further optimization of rehabilitation in which auditory components (like amplification and speech processing techniques in a hearing aid) and nonauditory components (like training) should be involved.

In the literature, speech recognition in unilateral hearing loss (UHL) listeners is measured in a sound field and in binaural conditions (Reeder et al. 2015; Vannson et al. 2015, 2017; Mondelli et al. 2016). These studies are very useful to provide information about the hearing abilities of UHL listeners in daily life situations. Vannson et al. (2015, 2017) have included participants with a wide range of hearing losses on the affected side. They presented speech and noise to the unaffected or affected ear in a sound field and found an effect of pure-tone average (PTA) on SRT. They also found that quality of life (measured by Speech, Spatial and Qualities of Hearing Scale) was significantly poorer for UHL subjects compared with NH subjects and that there was a correlation with PTA. In their research, all types of hearing loss were included, including conductive and retrocochlear hearing loss with different effects on speech recognition. Reeder et al. (2015) found differences in speech in quiet, speech in noise, and localization in children with UHL compared with their NH peers, but in their population, the affected ear had a profound hearing loss (average 100.8 dB HL). In the present study, we are interested in the effect of the cochlear hearing loss in one ear, to gain insight into specific effects of a cochlear hearing loss. To our knowledge, this is a new approach, not earlier described in the literature.

The premise of this study is that measuring SRT of both ears in listeners with UHL gives the opportunity to isolate auditory from nonauditory factors to a large extent. The cognitive and linguistic resources that can be exploited in the process of speech recognition are equal when stimuli are presented to either the unaffected ear (UHL+) or the affected ear (UHL−). Hence, the outcomes of psychophysical tests of both ears are equally influenced by top-down processing. The difference in scores for both ears within one UHL listener then is likely due to differences in bottom-up processing, that can be further subdivided into differences in audibility and suprathreshold deficits. With this approach, we attempt to reduce the effect of confounding factors that may have influenced earlier research studying the effect of peripheral hearing loss on speech recognition, that is, age, sex, education, cognition, or linguistic abilities.

The first hypothesis is that, in UHL listeners, speech recognition scores in quiet and in noise are better in UHL+ than in UHL−. This would imply that a difference in bottom-up processing does have impact on speech recognition. Audibility is an obvious factor for which it is expected that it has a large influence on speech recognition. However, it is furthermore expected that, given equal audibility, the affected side of UHL listeners needs more speech information to achieve the same scores as the unaffected side. This would imply that the reduced performance is not only due to audibility but also due to suprathreshold deficits. Finally, it is hypothesized that speech recognition scores of UHL+ are comparable with the scores of NH listeners. This implies that there is no compensation, or increased functioning, at the UHL+ due to the decreased functioning at the UHL−.

MATERIALS AND METHODS

Participants

Forty-four native-Dutch-speaking adult listeners participated in the present study. Fifteen listeners (age ranging from 24 to 62 years, mean 47 years; 3 men, 12 women) had normal hearing (NH), 19 listeners (age ranging from 26 to 78 years, mean 55 years; 7 men, 12 women) had unilateral sensorineural hearing loss (UHL), and 10 listeners (age ranging from 21 to 63 years, mean 48 years; 10 women) had bilateral symmetric sensorineural hearing loss (BHL). The UHL and BHL listeners were patients from the Audiology department of Amsterdam UMC, location VU University Medical Center.

NH was defined as air conduction thresholds ≤20 dB HL for all octave frequencies from 0.25 to 4 kHz. Audiometric criteria for impaired hearing were air conduction thresholds of 25 to 70 dB HL for all octave frequencies from 0.25 to 4 kHz. All listeners had air-bone gaps of ≤10 dB at frequencies 0.5, 1, and 2 kHz, had no history of ear surgery, and no history of retrocochlear pathology. UHL participants had one ear within the criteria of NH and one ear within the criteria of impaired hearing as defined above. NH and BHL participants had symmetrical hearing, which was defined as an asymmetry of ≤10 dB at any octave frequency between 0.25 and 4 kHz.

All participants gave informed consent and were paid a small gratuity for their participation. Ethic approval was obtained by the Medical Ethical Committee of VU University Medical Center.

Stimuli

Audiometry was performed with the Hughson-Westlake procedure (Carhart & Jerger 1959). Air conduction thresholds were measured at all octave frequencies from 0.25 to 8 kHz and bone conduction thresholds were measured at 0.5, 1, and 2 kHz. Hearing threshold was defined by PTA of 0.5, 1, 2, and 4 kHz.

Speech recognition was tested with words in quiet of the type consonant–vowel–consonant (CVC test, Bosman, Reference Note 2; Bosman & Smoorenburg 1995), and digit triplets in quiet and in noise (Digits-In-Noise test [DIN], Smits et al. 2013). The speech materials of Bosman and Smoorenburg (1995) consist of meaningful monosyllables of the CVC type (e.g., "bus"). The digit triplets consist of concatenated individually uttered digits (so the digit triplet had no coarticulation or prosody). All digits (i.e., 0 to 9) occurred.

Procedure

All tests were conducted in a sound-insulated room. Pure-tone audiograms were measured with a Decos audiometer (Decos Technology) and TDH-39 headphones. All other tests were conducted on a Dell personal computer, equipped with an external digital sound card (Sound Blaster Audigy, Creative Labs Technology Ltd.) and Sennheiser HDA-200 headphones (Sennheiser electronic GmbH & Co. KG). All tests were conducted monaurally; no signals were presented at the contralateral ear. Custom software (in Delphi) was developed at our department to conduct the tests.

The experiment started with pure-tone audiometry to confirm the participants hearing status. Next, the different speech recognition conditions were conducted. They consisted of (1) CVC in quiet, (2) DIN in quiet, (3) DIN at 65 dBA, (4) DIN at 80 dBA. They were labeled as CVCq, DINq, DIN65, and DIN80, respectively. For all groups (NH, UHL, and BHL), both ears were tested. The order was counterbalanced using a Latin square design both between and within the tests.

In the CVC test, lists of 12 words were presented at a fixed level. The first word of each list was presented for practice, after which 11 words, that is, 33 phonemes, remained. The percentage correct was based on the number of correctly repeated phonemes. As with conventional speech audiometry in a clinical setting, the performance-intensity curve was determined by measuring the percentage-correct score at several levels. The 50%-correct score was obtained from the performance-intensity curve by interpolation and is labeled as the speech recognition threshold (SRT). A step size of 10 dB around the SRT and 15 dB at levels well above the SRT was used to determine the complete performance-intensity curve. There were no practice runs.

The DIN test (Smits et al. 2013) consists of lists of 24 pseudorandomly chosen digit triplets. The SRT was determined by an adaptive procedure, where the level of the triplets was varied according to 1-down, 1-up method. In quiet, the signal level of a digit triplet was increased by 2 dB after an incorrect response and decreased by 2 dB after a correct response. In the noise condition, triplets were presented in long-term average (triplet) speech spectrum noise. The SRT was determined by the same adaptive procedure, where the signal to noise ratio (SNR) was increased by 2 dB after an incorrect response and decreased by 2 dB after a correct response. The SRT was determined by averaging across the presentation levels (in quiet) or SNR's (in noise) over the last 20 triplets. In DIN65 and DIN80, the SNR was varied adaptively, but the overall level was kept fixed to 65 and 80 dBA. To eliminate learning effects, 1 practice run of 24 triplets at 65 dBA in long-term average (triplet) speech spectrum noise was presented. We included the 65 dBA level because it represents speech levels in daily life situations. We also included 80 dBA to reduce the effect of audibility, where speech signals should be above-threshold.

A complete set of measurements was obtained for the individual ears of all 44 participants. The present set of measurements were part of a larger set, conducted at the same session.

Data Analysis

All statistical analyses were performed using SPSS statistical package 22 for Windows. Normal distribution was checked by Shapiro-Wilk test. For the separate participant groups, the SRTs of all four conditions (CVCq, DINq, DIN65, and DIN80) were approximately normally distributed. Mixed design analysis of variance (ANOVA) was used to account for the within-subject variable "ear" (best and worst test ear) and "condition' (CVCq, DINq, DIN65, and DIN80). Between subject variables were "group" (UHL, NH, and BHL), gender, age, and side of hearing loss. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2[5] = 17.10$, $p = <0.05$), therefore Greenhouse-Geisser correction is reported (epsilon = 0.42). Posthoc analyses have been performed with ANOVA, *t* tests (two sided) and linear regression. A *p* value of <0.05 was assumed to be significant.

RESULTS

Main effects were analyzed by mixed-design ANOVA. There was a significant main effect of ear (best/worst) on the test-score [$F(1,3) = 150.16$; $p = 0.001$]. There was also a significant main effect of the condition (CVCq/DINq/DING65/DIN80) on the test score [$F(1.25,3.74) = 238.54$; $p < 0.001$]. There was no significant effect of gender [$F(1,3) < 1$; $p = 0.984$], age [$F(23,3) <1$; $p = 0.907$] or side of hearing loss [$F(1,3) = <1$; $p = 0.755$]. There was a significant effect of group (UHL, NH, or BHL) [$F(2,3) = 10,68$; $p = 0.043$].

Duration of hearing loss varied from 0.5 year up to 25 years, but had no significant effect on interaural differences in SRT (diffSRT in dB) of any of the 4 conditions (ANOVA, $p > 0.76$ for all 4 conditions). Six UHL listeners used a hearing aid on the affected side on a daily basis. Of the remaining 13 listeners, who did not wear a hearing aid, 9 had tried a hearing aid in the past with negative result. The use of a hearing aid had no significant effect on diffSRT in any of the four conditions (ANOVA, $p > 0.53$ for all four conditions).

Group Level

In Table 1, the mean and standard deviation for the SRTs obtained in the CVCq, DINq, DIN65, and DIN80 condition are

TABLE 1. Speech reception thresholds

	NH			UHL+		UHL−		BHL	
	Mean (n)	SD	Literature	Mean (n)	SD	Mean (n)	SD	Mean (n)	SD
CVCq	27.3 (15)	3.7	21.6*	27.9 (19)	3.8	71.3 (19)	12.9	71.7 (10)	9.1
DINq	17.8 (15)	4.1	18.3†	18.2 (19)	3.0	58.7 (19)	13.8	58.5 (10)	8.8
DIN65	−9.1 (15)	0.9	−9.3‡	−8.5 (19)	1.0	−1.8 (11)	5.8	0.5 (7)	2.8
DIN80	−8.1 (15)	0.7	N.A.	−7.6 (19)	1.2	−2.6 (19)	3.4	−3.6 (10)	2.8

Mean and standard deviation for speech recognition thresholds in quiet and in noise. Measured with CVC words (CVCq) and digit triplets (DINq) in quiet and with digit triplets in stationary noise at overall level of 65 dBA (DIN65) and 80 dBA (DIN80). Results are shown for listeners with NH, UHL+, UHL−, and BHL.
Bosman and Smoorenburg (1995).
†Smits et al. (2013).
‡Smits et al. (2016).
BHL, bilateral hearing loss; CVCq, consonant–vowel–consonant words in quiet (dB A); DIN65, digit-triplets in noise at 65 dBA (dB SNR); DIN80, digit-triplets in noise at 80 dBA (dB SNR); DINq, digit-triplets in quiet (dB A); NH, normal hearing; UHL+, unaffected ear of unilateral hearing loss; UHL−, the affected ear of unilateral hearing loss.

given for NH, UHL+, UHL−, and BHL. Also given are the SRTs for listeners with NH that are reported in the literature, as a reference. Statistical analysis (ANOVA) showed significant differences between UHL− and UHL+, but no significant differences between UHL+ and NH or between UHL− and BHL. For both NH and BHL, posthoc analysis (Tukey's procedure) showed that SRTs obtained with the better ear (defined as better PTA) were equal to those obtained with the worse ear. Therefore, for NH and BHL, scores were pooled for both ears. For NH subjects, CVCq, DINq, and DIN65 thresholds were comparable to those reported in the literature (Bosman & Smoorenburg 1995; Smits et al. 2013). For DIN80, there were no reference data. In Table 2, p values of paired samples and independent t tests are presented.

It can be concluded that SRTs were worse for UHL− than for UHL+ in quiet and in noise. Furthermore, UHL+ and NH had comparable SRTs on all four conditions. Similarly, UHL− and BHL had comparable SRTs for all conditions, which were poorer than those for UHL+ and NH. The latter result was merely to show that the aim of selecting a group of BHL subjects with a hearing loss comparable with the UHL group had been met.

Audibility

The focus of the present study was the comparison of the UHL+ and UHL− ear, because the main aim was to exclude the influence of top-down processing as much as possible. Therefore, only results obtained with the UHL group are considered in this section. To investigate the role of audibility on speech recognition, the relation between PTA and SRT was explored. In Figures 1A, B, the relation between PTA (in dB HL) and SRT for CVCq (in dBA) and DINq (in dBA) is shown. Every UHL listener is represented twice, one point for UHL+ and one for UHL−. It is evident that both SRTs depend on PTA. A linear fit to the data results in an almost unity slope (SRT = 17.24 + 1.04 × PTA for CVCq and SRT = 7.74 + 0.99 × PTA for DINq). Note that, this relation is used every day in the clinic to compare the results of pure-tone audiometry with those of speech audiometry (CVC phonemes score). Extrapolation of the data in Figure 1A yields that for CVCq, a signal level of 17.2 dBA is needed to achieve 50% correct speech recognition with a hearing threshold of 0 dB HL. Similarly, extrapolation of the data in Figure 1B shows that for DINq, a signal level of 7.7 dBA is required for 50% correct at 0 dB HL. The difference in offset of 9.5 dB can be attributed to differences in complexity of the speech materials (e.g., open-set versus closed set).

In the speech-in-noise conditions, the overall signal level was kept constant at either 65 or 80 dBA. This implies that in subjects for which, due to the severity of their hearing loss, the DINq threshold was 65 dBA or higher, SRT for DIN65 theoretically cannot be reached. Indeed, it showed that DIN65 could be measured only in 11 of 19 subjects.

In Figures 1C, D, the relationship between PTA (in dB HL) and the SRT for DIN65 (in dB SNR) and DIN80 (in dB SNR) is shown including regression lines and R^2 values. The results showed that a larger hearing loss generally leads to higher (i.e., poorer) SRTs, but the slope is not equal to unity as for CVCq and DINq in Figures 1A, B. When we investigated the effect of PTA on SRT, we saw very high values in quiet ($R^2 = 0.961$ for CVCq and $R^2 = 0.959$ for DINq, linear regression, $p < 0.001$) and reasonable high values in noise (R^2 0.570 for DIN65 and R^2 0.703 for DIN80, linear regression, $p < 0.001$). Audibility

TABLE 2. Statistical analysis

	UHL+ vs. UHL−*		UHL+ vs. NH†		UHL− vs. BHL†	
	t	*p* Value	*t*	*p* Value	*t*	*p* Value
CVCq	**−14.16**	<0.001	−0.42	0.675	−0.10	0.924
DINq	**−12.59**	<0.001	−0.37	0.717	0.06‡	0.954
DIN65	**−5.90**	<0.001	−1.84	0.075	−0.96	0.350
DIN80	**−5.21**	<0.001	−1.38‡	0.180	0.09	0.929

Results that are significantly different (p < 0.004; Bonferroni correction is applied) are given in bold faces.
Paired samples t test.
†Independent t test.
‡Equal variances are not assumed.
BHL, bilateral hearing loss; CVCq, consonant–vowel–consonant words in quiet (dB A); DIN65, digit-triplets in noise at 65 dBA (dB SNR); DIN80, digit-triplets in noise at 80 dBA (dB SNR); DINq, digit-triplets in quiet (dB A); NH, normal hearing; UHL+, unaffected ear of unilateral hearing loss listener; UHL−, the affected ear of unilateral hearing loss listener.

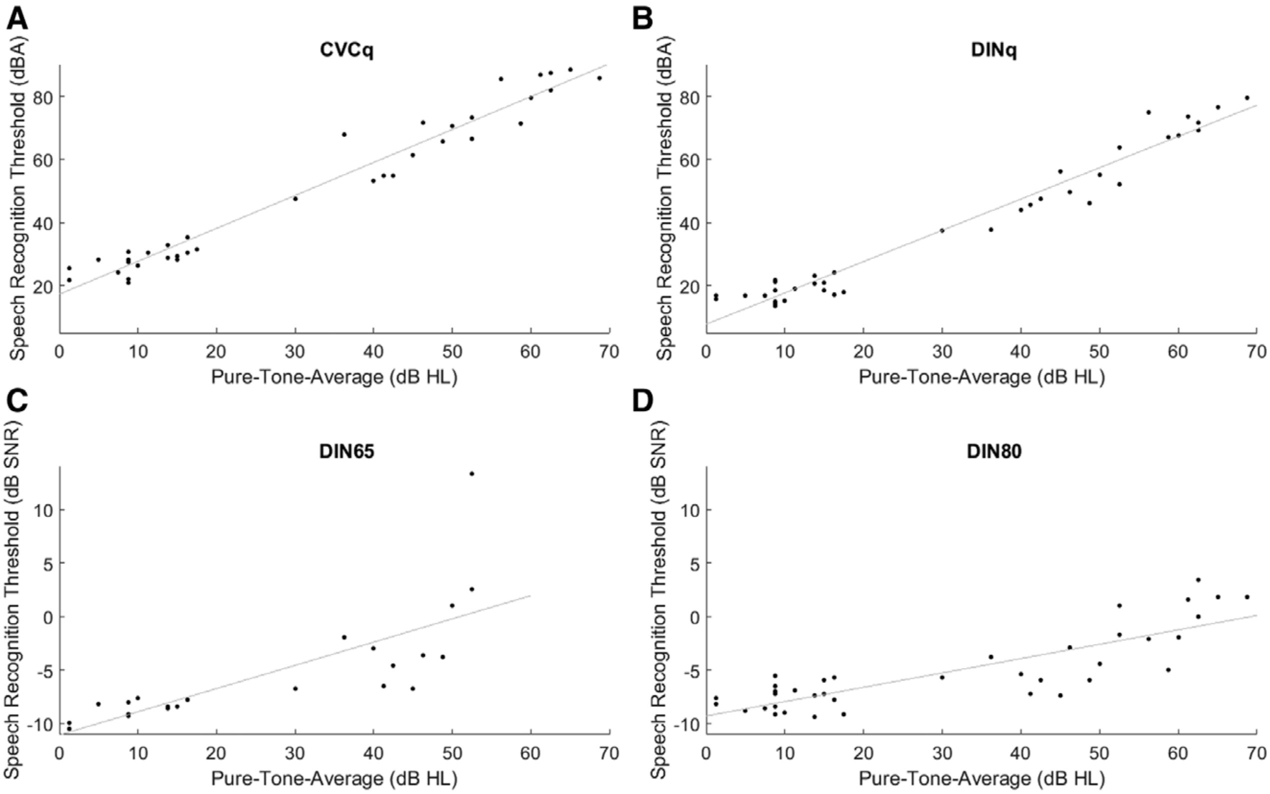

Fig. 1. SRT for unilateral hearing loss listeners in four speech recognition tests. A, CVCq; regression line: SRT = 17.24 + 1.04 × PTA (R^2 = 0.961). B, DINq; regression line: SRT = 7.74 + 0.99 × PTA (R^2 = 0.959). C, DIN65; regression line: SRT = −11.05 + 0.22 × PTA (R^2 = 0.570). D, DIN80; regression line: SRT = −9.27 + 0.13 × PTA (R^2 = 0.703). CVCq, consonant-vowel-consant words in quiet; DIN65, digit-triplets in noise at 65 dBA; DIN80, digit-triplets in noise at 80 dBA; DINq, digit-triplets in quiet; PTA, pure-tone average; SRT, speech recognition threshold.

still seemed to play a significant role, even at high stimulus levels, but suprathreshold processing deficits and top-down processing may confounded the results of speech understanding in quiet and noise.

To rule out the effect of top-down processing as much as possible, results between UHL+ and UHL− were compared within subjects. Figures 2A–D show the relation between the interaural difference in PTA (diffPTA in dB) and the difference in SRT (diffSRT in dB) for CVCq, DINq, DIN65, and DIN80. We found a strong relation between audibility and speech recognition in quiet (Figs. 2A, B; R^2 = 0.698 for CVCq [linear regression, $p < 0.001$], R^2 = 0.740 for DINq [linear regression, $p < 0.001$]). A less pronounced relation is found between audibility and speech recognition in noise (Figs. 2C, D; R^2 = 0.505 for DIN65 [linear regression, $p = 0.014$], R^2 = 0.375 for DIN80 [linear regression, $p = 0.005$]).

From this, we concluded that audibility still plays a role in noise, although suprathreshold deficits might explain part of the difference in outcome between quiet and noise. Note that the effect of top-down processing was reduced as much as possible due to the comparison of UHL+ with UHL−.

Speech Intelligibility Index

Because audibility still played a major role in our outcomes, we decided to use an alternative way to quantify audibility, by using the speech intelligibility index (SII) (S3.5, A 1997). The SII accounts for differences in importance of frequency bands for speech recognition. It ranges from 0 to 1, corresponding to the amount of available speech information. When performance on the outcome measure is fixed (e.g., 50% speech recognition, like in the adaptive procedures used in the present study), the SII value represents the relative amount of information the listener needs to achieve this level of performance. Hence, if the SII is larger for UHL− than for UHL+, this suggests suprathreshold deficits at UHL−. As shown by Rhebergen et al. (2010a), the SII has limitations, especially for the prediction of SRTs in quiet, where small variations in hearing threshold can result in considerable variations in SII.

We transformed the SRTs in Figures 1 and 2 to SII values, using the measured audiometric values for each ear. The SII was calculated in Mathworks Matlab 2016 for Windows. Scripts had been developed by the first author and were based on open-source scripts of the ASA Working Group S3-79 (Müsch, H. 2005) For the DIN65 and the DIN80 condition, the difference in SII between ears (diffSII) was calculated and the relation between diffSII and diffPTA is plotted in Figures 3A, B for DIN65 and DIN80, respectively. Statistical analysis showed that diffSII did not deviate significantly from 0 for DIN65 (paired *t* test, $p = 0.171$, n = 11), indicating that there was no significant difference in amount of speech information necessary for UHL+ and UHL− to achieve the same speech recognition performance in this task. However, for DIN80, the difference in SII had a significant positive value (mean difference of 0.051; paired *t* test; $p = 0.001$) for the same group of 11 UHL listeners. Also when we expanded the data by selecting all UHL listeners that could fulfill DIN80 (n = 19), we found significant higher SII for

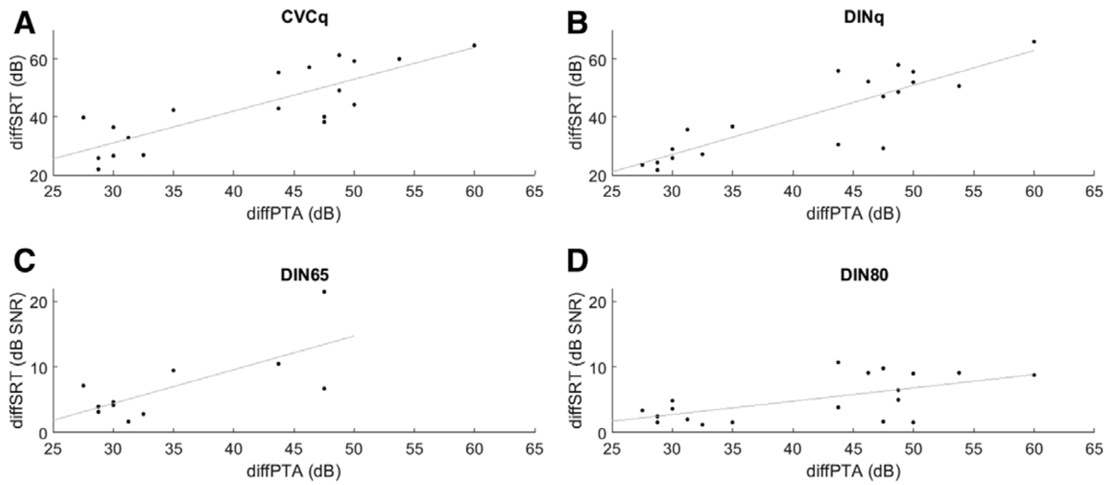

Fig. 2. DiffSRT between unaffected and affected ear of unilateral hearing loss listeners in four speech recognition tests. A, CVCq; regression line: SRT = −1.90 + 1.09 × PTA (R^2 = 0.698). B, DINq; regression line: SRT = −8.86 + 1.20 × PTA (R^2 = 0.740). C, DIN65; regression line: SRT = −11.00 + 0.51 × PTA (R^2 = 0.505). D, DIN80; regression line: SRT = −3.36 + 0.20 × PTA (R^2 = 0.375). CVCq, consonant-vowel-consant words in quiet; diffPTA, difference in pure-tone average between ears; diffSRT, difference in speech recognition threshold; DIN65, digit-triplets in noise at 65 dBA; DIN80, digit-triplets in noise at 80 dBA; DINq, digit-triplets in quiet; PTA, pure-tone average; SRT, speech recognition threshold.

UHL− than for UHL+ (mean difference of 0.033; paired *t* test, p = 0.032). This indicates that the impaired hearing side needs more information than the NH side to achieve 50% speech recognition at higher sensation levels.

DISCUSSION

The purpose of this study was to explore the specific effects of peripheral hearing loss (bottom-up processing) on speech recognition and to identify to what extent suprathreshold deficits play a role. The UHL data create an opportunity to separate these effects from top-down processing as much as possible. We found that at higher sensation levels, the affected ear needs more information to perform as well as the unaffected ear. Below, a stepwise attempt is made to embody our results.

Top-Down Processing

We aimed to rule out effects of top-down processing as much as possible by studying a group of listeners with UHL. As stated in the Introduction, the cognitive and linguistic resources that can be exploited in the process of speech recognition are assumed to be equal when stimuli are presented to either the unaffected ear (UHL+) or the affected ear (UHL−). Hence, the outcomes of psychophysical test on both ears are equally influenced by those top-down processes. So, to exclude (most of the) interindividual top-down processing, the results between ears, hence within subjects, are considered. In Figure 2, the interaural difference in SRT (diffSRT) is plotted against the interaural difference in PTA (diffPTA) for each individual UHL listener for CVCq, DINq, DIN65, and DIN80. The spread of the data points across the ordinate is larger in Figure 2A than in Figure 1A in which all data points are presented. This indicates that most of the variance is due to within-subject measurement error, instead of differences in top-down processing across subjects and, hence, that across-subject differences did not cause much variance. Another way to assess the effect of top-down processing in our data is by considering the residual errors in Figure 1. In each of the panels, two data points are produced by each individual subject, one for the UHL+ and one for the UHL−. If top-down processing had played a major role, one would expect that the deviation from the fitted line in Figure 1 (the residual error; that could be derived from Fig. 1) would be similar for both data points of the pair belonging to a subject. The data show that only in 7 of 19 cases, the residual errors

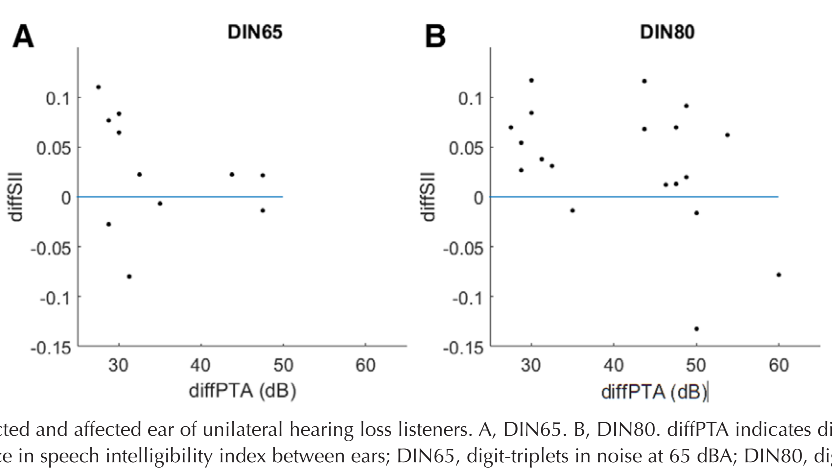

Fig. 3. DiffSII between unaffected and affected ear of unilateral hearing loss listeners. A, DIN65. B, DIN80. diffPTA indicates difference in pure-tone average between ears; diffSII, difference in speech intelligibility index between ears; DIN65, digit-triplets in noise at 65 dBA; DIN80, digit-triplets in noise at 80 dBA.

have the same sign (are either both positive or both negative). This analysis also indicates that the effect of top-down processing on the SRT is only small compared with the within-subject measurement error.

Audibility Versus Suprathreshold Deficits

In Figure 2, diffSRT is positive in all cases, indicating worse performance in the worse ear. Also there is a trend that diffSRT increases with increasing diffPTA. These trends between diffPTA and diffSRT for CVCq, DINq, DIN65, and DIN80 indicate that audibility plays a role in speech recognition performance. This effect is clear for CVCq and DINq, as is expected, but is still apparent for DIN65 and DIN80. As differences in top-down processing have been ruled out to a large extent, in these within-subject data, systematic differences in speech recognition in noise can be attributed to individual differences in suprathreshold processing. However, possible artifacts of inadequate quantification of hearing loss and hence audibility have to be ruled out first.

We initially quantified audibility in a rather straightforward way using a 4-frequency PTA (4-PTA) at hearing thresholds 0.5, 1, 2, and 4 kHz. This 4-PTA is widely used in the literature and has been shown to correlate well with CVC words (Bosman & Smoorenburg 1995) and DIN (Koole et al. 2016). Analyses with other measures of audibility (3-PTA [0.5, 1, and 2 kHz], 3-PTA [1, 2, and 4 kHz], or 2-PTA [1 and 2 kHz]) yield comparable results to the relations presented in Figures 1 and 2. Relative importance of frequencies for speech recognition is only partly taken into account by PTA and therefore we introduced SII results.

We found that the affected side needed more information to perform equally to the unaffected side as shown in Figure 3. Summers et al. (2013) showed from SII analyses of their results that differences in speech audibility across subjects would predict differences in speech scores of no greater than 10% at a given SNR. However, actual speech scores varied by as much as 80% across subjects, indicating that suprathreshold deficits also are of importance. However, they were not able to separate across-subject differences (age, cognitive skills, etc.) from suprathreshold because they compared two study groups: listeners with normal and impaired hearing, respectively.

With the current dataset, we can estimate the specific effect of suprathreshold deficits on speech recognition more purely. This can be done by comparing the measured SRT at UHL− to the expected SRT at UHL−; the latter being calculated under the assumption that the SII at UHL− should be equal to UHL+ to achieve 50% recognition performance. Based on the equal-SII assumption, for the 11 subjects, an average (theoretical) decrease in performance of 3.1 dB SNR in UHL− compared with UHL+ (range −7.0 to 0.6 dB SNR) is obtained. The average difference in the actual (measured) SNR for UHL− and UHL+ is 5.2 dB SNR (range −10.5 to −1.0 dB SNR). This indicates that for this subgroup and this condition, that suprathreshold deficits (2.1 of 5.2 dB SNR) and audibility (3.1 of 5.2 dB SNR) are both a substantial part of SNR loss.

UHL Versus NH and BHL Listeners

In this section, we relate results of our UHL group to groups of NH and BHL listeners, and earlier published study. Results have shown that the outcome of all four conditions (CVCq, DINq, DIN65, and DIN80) were not significantly different between NH and UHL+.

Earlier published study by Bosman and Smoorenburg (1995) showed 21.6 dBA as the mean intensity for 50% correct speech recognition in the CVCq test for NH listeners. We found 27.3 dBA in our data of the NH group which is significantly higher (1-sample *t* test; $p < 0.001$). This difference can be fully explained in terms of the average hearing level of their group and our group (approximately 0 versus 8.3 dB HL averaged over 0.5, 1, 2, and 4 kHz). Smits et al. (2016) found a DIN65 of −9.3 dB SNR with the HDA-200 headphone for NH, which is not significantly different from our findings in NH of −9.1 dB SNR (1-sample *t* test; $p = 0.424$).

For DIN80, no reference data were available in the literature. We found significantly worse performance in DIN80 compared with DIN65 in NH ($p < 0.001$, paired *t* test, n = 11). Rhebergen et al. (2010b) reported no difference in dB SNR at levels 65, 75, and 85 dBA. The difference with our findings might be explained by differences in speech material (digit triplets versus sentences) and level of the target and masker signal (overall-fixed versus noise level-fixed).

From comparing NH with UHL+, we can conclude that speech recognition of NH and UHL+ is comparable when monaurally presented. This finding is in line with the earlier published studies of Rothpletz et al. (2012) and Firszt et al. (2017). UHL thus is not compensated by better hearing acuity of the unaffected ear. Our findings of UHL− are not easily related to BHL due to the wide range of hearing thresholds in both groups. Nevertheless, we see comparable results of UHL− and BHL on all four conditions.

Participants

Our idea was to reduce the of effect top-down processing by using UHL listeners. Instead of comparing the affected and unaffected ear in listeners with UHL, one could measure only unaffected ears in NH listeners and compare normal performance to performance with manipulated stimuli that mimic hearing loss, for example, by introducing masking noise, expansion, or even signal gating. However, this would introduce a number of uncertainties that might interact with top-down processing. With the choice of UHL, we used a naturally occurring condition where it is known how the signal is delivered to the cochlea (or at least the eardrum). The use of this natural listening condition, without manipulation of the signal, circumvented potential learning effects of a new condition. The results showed that in the present experiment, the effect of top-down processing is very small. The specific sample of participants with a UHL gives us the opportunity to reduce the influence of factors that might have affected the outcomes of earlier research. Normally, groups need to be matched on factors like age, sex, and education level, but when comparing both ears of one individual, these factors are all equal. With the benefit of hindsight, we would have liked to include more participants with a mild to moderate hearing loss to increase the number of participants that could fulfill all four conditions and make our analyses more powerful. However, introducing 8 additional participants in DIN80 with more severe hearing loss did not change outcome.

There is evidence for cortical reorganization in patients with unilateral sensorineural hearing loss (Yang et al. 2014; Fan et al. 2015). A relation with degree of hearing loss (Alfandari et al. 2018) and duration of hearing loss (Zhang et al. 2018) is reported. Other studies suggested the possibility of compensatory reorganization (Bilecen et al. 2000; Munro 2008). Finally, Mishra et al. (2015) even suggested that the temporal resolution of the normally hearing ear in UHL is affected by the contralateral hearing impairment. However, the impact of these forms of cortical organization on speech recognition is poorly understood. Most studies in the literature included patients with a profound hearing loss (>70 dB HL) and all kinds of etiology, including retrocochlear pathologies like acoustic neuroma and resection of the auditory nerve. In the present study, we used participants with relatively mild sensorineural hearing loss. The UHL− ear is still stimulated by all types of sounds in daily life in contrast to most participants in the literature mentioned above. We therefore expect that potential cortical reorganization, induced by the hearing loss on one side, is equal to or less for our UHL participants compared with the studied populations.

Tests

Hearing thresholds and speech recognition can be measured in many ways. We measured hearing thresholds using pure-tone audiometry with a −10/+5 step procedure that is used in many clinics (Carhart & Jerger 1959). Alternative choices were a Bekesy-tracking or a smaller step size. With these methods, a more precise hearing threshold could have been determined and might have resulted in better estimations of our SII results. On the other hand, these tests are more time consuming and the results of the Bekesy-tracking are more influenced by personal style (subjectively defined threshold). Given these arguments, we think that the tests chosen to measure hearing threshold are the most suitable for the goal of the present study.

Several speech recognition tests are available, using phonemes, words (meaningful or nonsense), digits, or sentences as stimuli. We decided to use CVCs and digits, because CVC words are regularly used in clinical practice and DIN is minimally influenced by linguistic skills, is quick, and can be repeated unlimitedly (Smits et al. 2013). For future research, it would be interesting to repeat the current experiment using sentence materials and compare these results to the current data. Based on Figures 1 and 2, we estimate that top-down processing had almost no influence on understanding of words and digit triplets. In sentence material, top-down processing may be more important and may reveal more variation.

In daily life, background noise is often fluctuating instead of stationary. We know from, for example, Rhebergen et al. (2010b) that SNR in fluctuating noise is largely dependent on presentation level. Repeating our measurements in fluctuating noise would be the next step to mimic daily life situations even more. It should however be noted that controlling for audibility will be much more challenging.

The absence of cross-hearing of the speech signal is not guaranteed when signals above threshold are presented to the affected ear. The minimal interaural attenuation of the HDA200 headphone, that was used of the speech-recognition experiments, is 46 dB at 2 kHz and the average attenuation is 59 dB (frequency range 0.5 to 4 kHz; Brännström & Lantz 2010). We maximized hearing threshold at 70 dB HL because of interaural attenuation and measured masked air conduction thresholds if interaural attenuation could be of influence. No threshold shifts were found when masking the air conduction threshold. It, therefore, is highly unlikely that the unaffected ear contributed to the speech recognition in the affected ear.

In our assessment of speech recognition, we measured monaurally without masking of the contralateral ear. Introducing a masking noise on the contralateral ear would introduce a new parameter that could influence our results. For instance, summation of the noises at both ears might make the test easier, because of integration of the noises in the brain. If interaural attenuation had played a role in our study, then actual SII for UHL− would be higher and diffSII would be even larger. This would mean that we underestimate the effect of suprathreshold deficits. However, it would still support our conclusions that suprathreshold deficits significantly influence speech recognition.

Clinical Relevance

People with sensorineural hearing loss, wearing hearing aids, listen to signals consisting of target speech and maskers that are above hearing threshold. The limitation of audibility is (partly) solved by the amplification of these environmental sounds. From our study, it can be concluded that suprathreshold deficits have an important effect on speech recognition in this situation, resulting in the need for a higher SNR to obtain speech recognition performance scores similar to those for NH. For the UHL subjects in the present experiment, we showed that suprathreshold deficits result in the need for an increase of about 2.1 dB in SNR. This increase is large, compared with the effect of most signal processing strategies in modern hearing aids (Dillon 2012). This increase is also large compared with the total loss in SNR (5.2 dB). In clinical practice, it should be realized that rehabilitation of sensorineural hearing loss is only partly successful. To date, it is not really possible to measure the specific contribution of suprathreshold deficits in the clinic, which would be helpful in counseling and guiding the technical rehabilitation approach. Expanding the work of this study looks promising. Finding appropriate hearing rehabilitation techniques that can compensate for specific deficits is another challenge for both experimental and clinical audiology.

CONCLUSIONS

In this study, utilizing a group of listeners with unilateral sensorineural hearing loss, we showed that the influence of audibility on speech recognition outcomes is large, even when speech is well above threshold. Moreover, by using the SII, we showed that the affected ear needs more speech information than the unaffected ear to achieve equal performance. Individual differences in top-down processing were excluded by the selection of this population for this study. The difference in outcome between the ears of UHL listeners can be attributed to suprathreshold deficits. These suprathreshold deficits might influence speech recognition in quiet to some extent, but definitely influence speech recognition in noise when target and masker are audible, as in the case of hearing aid use. The present study population had on average a reduced SRT of 5.2 dB SNR for UHL− compared with UHL+. The average contribution of suprathreshold deficits to this reduction was estimated at 2.1 dB SNR. Further research is necessary to provide more insight in the specific underlying mechanisms that play a role and to apply this knowledge in rehabilitation of persons with hearing impairment.

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The authors have no conflicts of interest to disclose.

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Erratum

Residual Cochlear Function in Adults and Children Receiving Cochlear Implants: Correlations With Speech Perception Outcomes: Erratum

In the article that appeared on pages 577–591 of the May/Jun 2019 issue of *Ear and Hearing,* "Residual cochlear function in adults and children receiving cochlear implants: correlations with speech perception outcomes", there was an error in the third author's name.

The correct name is Margaret Dillon instead of Megan T. Dillon.

This error does not change the results of the research. The authors apologize for the error.

Reference

Fontenot, T. E., Giardina, C. K., Dillon, M. T., et al. (2019). Residual cochlear function in adults and children receiving cochlear implants: correlations with speech perception outcomes. *Ear Hear*, *40*, 577–591.