Beyond the audiogram: Influence of supra-threshold deficits associated with hearing loss and age on speech intelligibility

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Sensorineural hearing loss and greater age are associated with poor speech intelligibility, especially in the presence of background sounds. The extent to which this is due to reduced audibility or to supra-threshold deficits is still debated. The influence of supra-threshold deficits on intelligibility was investigated for normal-hearing (NH) and hearing-impaired (HI) listeners with high-frequency losses by limiting the effect of audibility. The HI listeners were generally older than the NH listeners. Speech identification was measured using nonsense speech signals filtered into low- and mid-frequency regions, where pure-tone sensitivity was near normal for both groups. The older HI listeners showed mild to severe intelligibility deficits for speech presented in quiet and in various backgrounds (noise or speech). Overall, these results suggest that speech intelligibility can be strongly influenced by supra-threshold auditory deficits.

INTRODUCTION

Both sensorineural hearing loss and greater age are associated with poorer-than-normal speech intelligibility (for reviews, see George *et al.*, 2006; Moore, 2007; Rhebergen *et al.*, 2010a; 2010b), especially for speech presented in background sounds. Some authors have suggested that the problems arise primarily from reduced audibility (e.g., Desloge *et al.*, 2010; Humes *et al.*, 1987; Lee and Humes, 1993; Zurek and Delhorne, 1987), i.e., from the fact that parts of the speech cannot be heard at all. Others have suggested that the problems arise not only from reduced audibility, but also from supra-threshold deficits that lead to perceived distortion or lack of clarity of the speech signal (e.g., Dreschler and Plomp, 1980; 1985; Glasberg and Moore, 1989; Plomp, 1978; 1986), i.e., from a reduced ability to discriminate the acoustic features of the speech, despite it being audible. The studies reviewed here aimed at investigating specifically the influence of supra-threshold deficits on the intelligibility of speech.

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Many studies have attempted to tease apart the contribution of reduced audibility and supra-threshold auditory deficits to speech intelligibility, especially for speech in complex backgrounds (e.g., Bernstein and Grant, 2009; Christiansen and Dau, 2012; Léger *et al.*, 2012b; Rhebergen *et al.*, 2006; Strelcyk and Dau, 2009). In many studies, reduced audibility (as estimated using audiometric thresholds) was not sufficient to explain the deficits of the hearing-impaired (HI) and/or elderly listeners (e.g., Bernstein and Grant, 2009; Dubno *et al.*, 2002; Füllgrabe *et al.*, 2015; Grose *et al.*, 2009; Hopkins and Moore, 2011; Horwitz *et al.*, 2002; Humes, 2002; Lorenzi *et al.*, 2006; Neher *et al.*, 2012; Sheft *et al.*, 2012; Summers *et al.*, 2013). Several supra-threshold deficits have been identified, including reduced frequency selectivity and reduced temporal processing (especially processing of the temporal fine structure [TFS] of the signal); see Moore (2007, 2014) for reviews. However, in some other studies, audibility has been suggested to fully explain the deficits of the HI listeners (e.g., Desloge *et al.*, 2010; Phatak and Grant, 2012). Thus, it is still unclear to what extent supra-threshold deficits contribute to the speech intelligibility deficits of the elderly and/or HI listeners. The goal of the studies reviewed here was to estimate the influence of supra-threshold deficits while controlling for the effect of audibility, therefore disentangling those two factors.

To control for, or at least reduce the influence of audibility and level differences of the stimuli for normal-hearing (NH) and HI listeners, speech intelligibility was compared for stimuli filtered into frequency regions where the audiometric thresholds were normal or near-normal for both groups. The results of previous studies using this approach (e.g., Horwitz *et al.*, 2002; Strelcyk and Dau, 2009) suggested that HI listeners with a high-frequency hearing loss could have speech processing deficits at lower frequencies. Several studies (Léger *et al.*, 2012b; 2012c; 2014) conducted using this approach are reviewed here. Note that the HI listeners were often older than the NH listeners; the effects of age are considered in the analyses that follow.

METHODS

Listeners

Listeners were informed about the goals of the studies and provided written consent before their participation. All studies were approved by French Regional Ethics Committee. Listeners were native French speakers and had no history of cognitive impairment or psychiatric disorders. A total of 112 listeners were tested in the studies reported here. Listeners were classified as NH or HI, based on their audiometric thresholds. Individual and mean audiometric thresholds are shown in Fig. 1.

A total of 63 NH listeners were tested. They had normal (≤20 dB HL) audiometric thresholds for octave-spaced frequencies between 0.125 and 8 kHz, except for 5 older listeners with audiometric thresholds of 25 dB HL at 6 and/or 8 kHz. The NH listeners were aged 20 to 61 years (mean=33 years, median 25 years, SD=13 years).

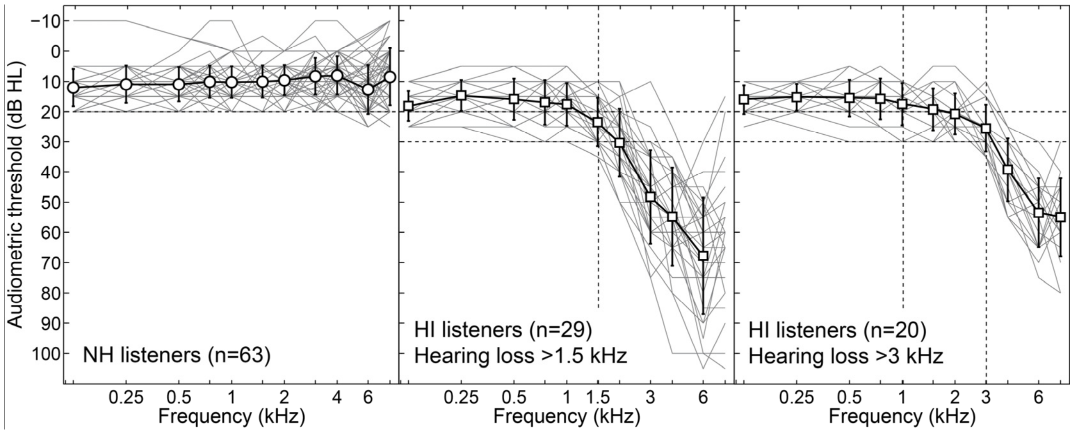

Fig. 1: Audiometric threshold (in dB HL) as a function of frequency for the NH listeners (left panel) and HI listeners. The HI listeners had near-normal audiometric thresholds up to either 1.5 kHz (middle panel) or 3 kHz (right panel), and a hearing loss above that frequency. In each panel, the grey lines show individual audiograms, and the thick black line shows the average audiogram (error bars: standard deviation, SD). The horizontal dotted lines show the limits of normality (20 dB HL) and near-normality (30 dB HL) for audiometric thresholds. The vertical dotted lines show the limits of some of the frequency regions of test for the HI listeners (see text).

A total of 49 HI listeners were tested. They had normal (≤20 dB HL) or near-normal (≤30 dB HL) audiometric thresholds for octave frequencies between 0.125 kHz and a cutoff frequency N_f, and a moderate to severe hearing loss at higher frequencies. The value of N_f was 1.5 kHz for 29 listeners and 3 kHz for the remaining 20 listeners. All losses were of sensorineural origin, as confirmed by the absence of air-bone gaps in the audiometric thresholds. The HI listeners were aged 20 to 76 years (mean=59 years, median=60 years, SD=13 years). An analysis of variance (ANOVA) unsurprisingly confirmed that the HI listeners were older than the NH listeners [$F(1,110)=104$, $p<0.001$]. An ANOVA was conducted on the pure-tone-averages in the low-frequency regions (up to 1.5 and 3 kHz), later referred to as PTA-f. Despite attempts at matching audiometric thresholds, the HI listeners had higher PTA-f than the NH listeners [$F(1,110)=79$, $p<0.001$]. On average, there was an 8-dB difference in PTA-f between the NH (mean=10 dB HL, SD=4 dB) and HI (mean=18 dB HL, SD=5 dB) listeners.

Speech materials

The methods used to measure speech intelligibility were similar across the studies reviewed here (Léger *et al.*, 2012b; 2012c; 2014). The reader is referred to those studies for details. Intelligibility was measured for speech signals filtered into three frequency regions. For the "*low-frequency region*", signals were low-pass filtered at 1.5 kHz. For the "*mid-frequency region*", signals were band-pass filtered between 1 and 3 kHz. For the "*low+mid-frequency region*", signals were low-pass filtered at

3 kHz. To prevent off-frequency listening, the filtered speech signals were always presented with a speech-shaped noise (SSN) filtered into the frequency region(s) outside of the region of test (e.g., above 1.5 kHz for speech low-pass filtered into the low-frequency region). This off-frequency noise was presented at a signal-to-noise ratio (SNR) of +12 dB. The HI listeners with a hearing loss above 1.5 kHz were tested only using the low-frequency region.

The speech signals were 48 Vowel-Consonant-Vowel (VCV) stimuli, each spoken twice by a female and a male native French speaker. Each set was composed of 16 consonants combined with three vowels. The four sets of VCVs (male and female speakers, two repetitions each) were used to generate a speech-shaped-noise (SSN). Note that in Léger *et al.* (2014), listeners were tested with the VCVs spoken by the male speaker only, the remaining VCVs being used as maskers (see below).

The filtered speech signals were presented at 65 dB SPL, except for HI listeners whose PTA-f was above 20 dB HL, in which case a frequency-independent gain equal to half the PTA was applied to (attempt to) restore audibility.

Background stimuli

The filtered speech signals were presented either in quiet (apart from the noise designed to limit off-frequency listening), or in an unmodulated or a modulated background. The unmodulated background was a SSN. The characteristics of the modulated backgrounds are described below. All listeners were tested with speech presented in quiet and in the unmodulated background; which listeners were tested with the various modulated backgrounds is reported below. Backgrounds were presented at fixed SNRs of −6, −3, and 0 dB. Backgrounds were filtered into the same frequency region as the speech signals they were presented with.

There were three types of modulated background. *"Backgrounds modulated in amplitude"*: a SSN was modulated in amplitude using an 8-Hz rectangular wave (modulation depth of 100%, random starting phase). Two duty cycles (DC, the percentage of time for which the masker was at full amplitude) were used to assess the effect of the duration of the temporal dips: 25% ("long dips") and 50% ("short dips"). "*Backgrounds modulated in spectrum"*: a SSN was passed through 32 non-overlapping gammatone filters each with a bandwidth of 1 ERB_N (equivalent rectangular bandwidth of the auditory filter for young listeners with normal hearing, Glasberg and Moore, 1990), and the outputs of the filters were multiplied by zero or 1 to introduce a spectral modulation. For "narrow dips", the pattern was 1, 0, 1, 0, 1, 0, 1, …, for "medium dips" the pattern was 1, 1, 0, 0, 1, 1, 0, 0, …, and for "wide dips" the pattern was 1, 0, 0, 0, 1, 0, 0, 0, 1, …. The value assigned to the lowest filter was randomised, thereby randomising the phase of the modulation. "*Speech*": VCVs were spoken by the female speaker (one VCV was chosen randomly for each trial). The fundamental frequency (f0) of the interfering speech was processed to assess the effect of the f0 separation between the target (male) and the interfering (female) speaker: the f0 separations were about 1 octave ("large f0 separation"), 3 semitones ("medium f0 separation"), and 1 semitone ("small f0 separation").

Procedure and analyses

In all studies, speech intelligibility was assessed by measuring consonant identification. Listeners were first tested with unfiltered VCVs in quiet, to familiarise them with the task; all listeners achieved scores of 80% correct or above. They were then tested with background sounds in a semi-random order (see each study for details).

Scores were converted into rationalized arcsine units (RAU; Studebaker, 1985) to make the data more suitable for ANOVAs. Because all listeners were not tested in the same frequency regions and background conditions, analyses on the results obtained by all listeners were not conducted here; the effects discussed below are supported by the analyses conducted for each study separately. Within each study and for each frequency region, ANOVAs were conducted on the scores with factors group (NH and HI) and condition (see papers for details). The influence of PTA-f and age was generally assessed using correlation analyses.

RESULTS AND DISCUSSION

Speech intelligibility scores

Consonant identification scores (hereafter referred to as "scores") are shown in Fig. 2. Scores are shown in each background condition, for NH and HI listeners (slight offset between the two groups, shown in black and white, respectively), and for all frequency regions (slight offset between the regions, and coded by the symbols). Conclusions were similar for the different SNRs tested; therefore, in Fig. 2, individual scores were averaged over different SNRs.

The older HI listeners had poorer scores than the NH listeners in most conditions, despite the fact that both groups were tested in frequency regions of normal or near-normal audibility. These findings support the hypothesis that supra-threshold deficits can lead to speech intelligibility deficits, even in the absence of a reduction in audibility. This is consistent with several studies in which speech intelligibility deficits were reported under conditions where audibility was normal or near-normal, for HI and/or elderly listeners (e.g., Füllgrabe *et al.*, 2015; Grose *et al.*, 2009; Horwitz *et al.*, 2002; Lorenzi *et al.*, 2009; Strelcyk and Dau, 2009).

There was large variability in the scores of the HI listeners in all conditions, with deficits ranging from mild to severe (up to ~60 RAU, relative to the average for the NH listeners). This confirms that HI listeners with similar audiograms can present with a wide range of speech intelligibility deficits. Large deficits were observed even for HI listeners with near-normal audiometric thresholds up to 3 kHz (see, for example, the results for the two HI listeners with the lowest scores in quiet in Fig. 2 – for the mid-frequency region). Thus, a clinically normal or near-normal audiogram up to 3 kHz does not ensure that speech intelligibility is normal.

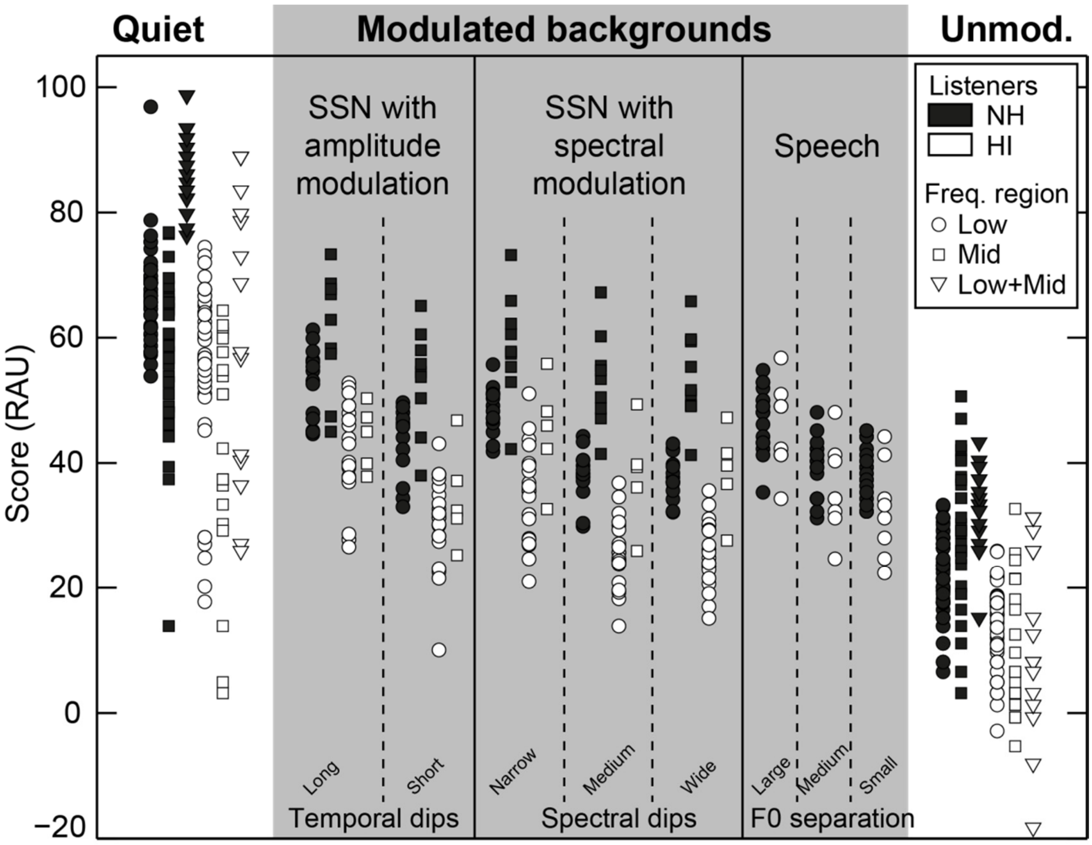

Fig. 2: Scores (in RAU) for the different background conditions: quiet, modulated backgrounds, or unmodulated backgrounds ("unmod."). The three different types of modulated backgrounds are specified at the top of the grey area, and for each type of modulated background, the different conditions (sizes of the dips or f0 separation) are identified at the bottom. Scores are shown in black for NH listeners and in white for HI listeners, and the symbols show the region of test (see legend). Within each condition (separated by the vertical lines), the results are slightly offset between listener groups and region of test.

The deficits of the HI listeners were generally larger for speech presented in background sounds than in quiet (see Fig. 2). This was true for all backgrounds except speech, for which the deficits of the HI listeners were mild. However, this might be due to the small sample sizes; see discussion in Léger *et al.* (2014). For the noise backgrounds, the deficits of the HI listeners were similar across different types of backgrounds. Notably, the differences in scores between unmodulated and modulated noises did not differ significantly for the NH and HI listeners tested by Léger *et al.* (2012b). In other words, the HI listeners did not show reduced "masking release" (or "release from modulation masking"; Stone *et al.*, 2011). This is at odds with studies suggesting that hearing loss and/or age can reduce masking release (for a review, see

Léger *et al.*, 2012d). It may be the case that suprathreshold deficits were less severe for the HI listeners tested here than for listeners showing moderate/severe hearing losses in the tested frequency regions, and that this difference explains the discrepancies in the masking release deficits. Taken together, those results suggest that in frequency regions of near-normal audiometric thresholds, supra-threshold deficits can lead to speech intelligibility deficits that are larger for speech in background sounds than in quiet, but this reflects a global deficit, not related to the type of background.

Origin of the speech intelligibility deficits

As suggested earlier, the deficits of the HI listeners in frequency regions of near-normal audiometric thresholds may have been caused by supra-threshold deficits. It may be the case that the high-frequency hearing losses were associated with supra-thresholds deficits, including in the low-frequency region. However, the speech deficits of the HI listeners were generally not related to the severity of their high-frequency hearing loss (that is, there was generally no significant correlation between scores and the PTA in the high-frequency regions of hearing loss). It may also be the case that the supra-threshold deficits were associated with age, given that the HI listeners were generally older than the NH listeners. The differences between the groups may also be the consequence of differences in PTA-f in the frequency region of test. These non-mutually exclusive hypotheses are discussed below.

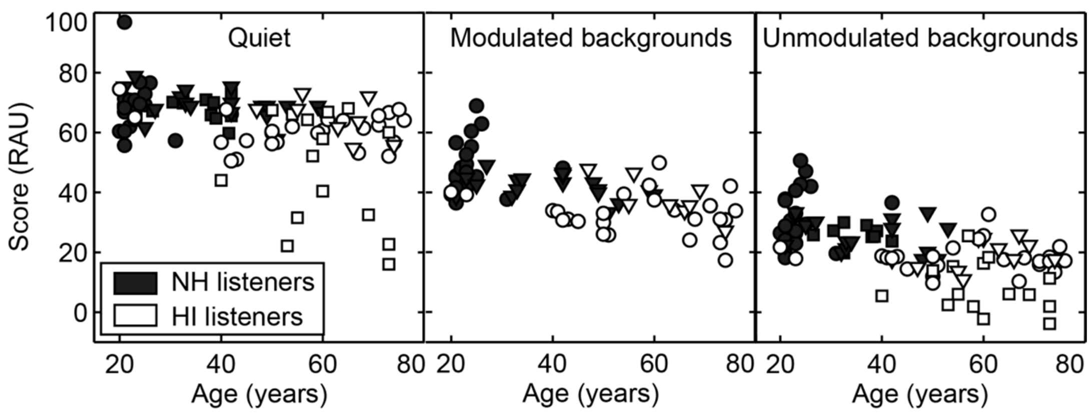

Fig. 3: Scores (in RAU) as a function of age (in years), averaged within the following background conditions: quiet, modulated backgrounds, unmodulated backgrounds. Scores for NH and HI listeners are shown in black and white, respectively. For each panel, scores were averaged within all frequency regions, background conditions and SNRs tested for a given listener. The symbols show in which study a given listener was tested: circles for Léger *et al.* (2012b; low- and mid-frequency regions), squares for Léger *et al.* (2012c; all frequency regions) and triangles for Léger *et al.* (2014; low-frequency region).

Greater age has been shown to have a deleterious effect on speech intelligibility (e.g., Arehart *et al.*, 2011; Dubno *et al.*, 2002; Grose *et al.*, 2009; Vongpaisal and Pichora-Fuller, 2007), as well as on many supra-threshold auditory abilities (e.g., Füllgrabe, 2013; Füllgrabe *et al.*, 2015; Harris *et al.*, 2008; He *et al.*, 2007; 2008; Strelcyk and Dau, 2009). As illustrated in Fig. 3, there was a global relationship between scores and age. However, the effects of age and hearing loss were generally confounded in the studies reviewed here (see Fig. 3: oldest listeners tend to be HI listeners, and vice versa; see Methods section). Analyses of the effect of age and the relationship between age and scores were carried out in all the studies reviewed here, but the conclusions were inconsistent across studies. Therefore, the effect of age on those results remains unclear. It could be the case that the speech intelligibility deficits of the HI listeners resulted largely from supra-threshold auditory deficits caused by factors associated with aging.

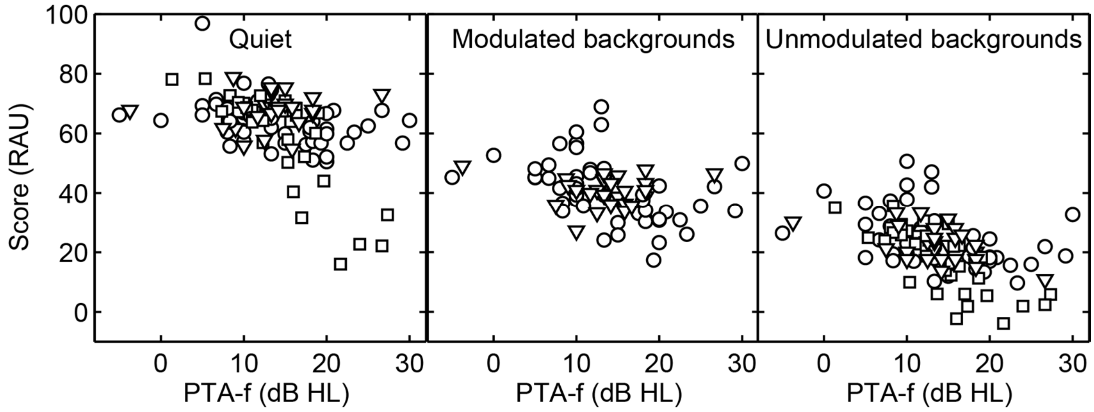

Fig. 4: Scores (in RAU) as a function of PTA-f (in dB HL) averaged within the following background conditions: quiet, modulated backgrounds, unmodulated backgrounds. Otherwise as Fig. 3.

The influence of audibility was assumed to be limited in the studies reviewed here, since all listeners were tested in frequency regions of near-normal audiometric thresholds and the speech was amplified for HI listeners with PTA-f above 20 dB HL. However, it remains unclear whether slightly increased audiometric thresholds in the tested frequency region were related to the speech identification deficits demonstrated by the HI listeners. As illustrated in Fig. 4, there generally was a relationship between PTA-f and speech intelligibility (see papers for details). This might indicate an influence of audibility. To assess whether the results were influenced by differences in the audibility of the target speech across listeners, extended speech intelligibility index (ESII; Rhebergen *et al.*, 2006; Rhebergen and Versfeld, 2005) values were computed by Léger *et al.* (2012b) for each listener. The ESII values were not correlated with the scores for either the NH or HI listeners, suggesting that the deficits demonstrated by the HI listeners were not due to small audibility differences.

However, the ESII may not give accurate predictions of intelligibility for those conditions. Therefore, the contribution of small audibility differences remains uncertain. It is possible, indeed likely, that the correlation between scores and PTA-f values occurred because higher audiometric thresholds are associated with larger supra-threshold deficits, which could reduce speech intelligibility without any influence of audibility.

Nature of the supra-threshold deficits

There are several candidate supra-thresholds deficits that might have affected the older HI listeners. Frequency selectivity can be slightly reduced for HI listeners at frequencies where the audiometric thresholds are normal or near-normal (for a review, see Léger *et al.*, 2012a). A simulation study (Léger *et al.*, 2012a) using spectral smearing with NH listeners, suggested that a slight reduction of frequency selectivity could lead to small intelligibility deficits in similar testing conditions. Furthermore, measurement of otoacoustic emissions suggested that outer hair cell functioning was related to the speech intelligibility deficits of the HI listeners tested by Léger *et al.* (2012c). However, slightly reduced frequency selectivity could not entirely explain the deficits demonstrated by the HI listeners (Léger *et al.*, 2012a). This is consistent with the result of Strelcyk and Dau (2009), who did not find any correlation between frequency selectivity and speech intelligibility for stimuli filtered into frequency regions of normal audibility. Therefore, it may be the case that other supra-threshold deficits are involved, for example in the processing of TFS cues. Indeed, both age and hearing loss have been shown to be associated with poorer TFS processing, which can contribute to intelligibility deficits for speech in background sounds (for a review, see Moore, 2014). However, in the studies reviewed here, there was no evidence in favour of or against an influence of impaired TFS processing on the deficits demonstrated by the (elderly) HI listeners for speech presented in background sounds. Therefore, the potential contribution of reduced TFS processing remains unclear.

It may also be the case that central factors played a role in the deficits of the HI listeners. Nonsense syllables were used in all studies to minimise the role of higher-level cognitive and linguistic processing. However, an influence of higher-level factors cannot be ruled out.

CONCLUSIONS

To control for the influence of reduced audibility, speech identification was measured using nonsense speech signals filtered into low- and mid-frequency regions, where pure-tone sensitivity was near normal for both (younger) NH and (older) HI listeners. The older HI listeners showed mild to severe intelligibility deficits for speech presented in quiet and in various backgrounds (noise or speech). Overall, these results suggest that speech intelligibility can be strongly influenced by supra-threshold auditory deficits associated with hearing loss and/or age, in the absence of reduced audibility.

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