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## Research Paper

## How do aging and age-related hearing loss affect the ability to communicate effectively in challenging communicative conditions?

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## ABSTRACT

This study investigated the relation between the intelligibility of conversational and clear speech produced by older and younger adults and (a) the acoustic profile of their speech (b) communication effectiveness. Speech samples from 30 talkers from the elderLUCID corpus were used: 10 young adults (YA), 10 older adults with normal hearing (OANH) and 10 older adults with presbycusis (O AHL). Samples were extracted from recordings made while participants completed a problem-solving cooperative task (diapix) with a conversational partner who could either hear them easily (NORM) or via a simulated hearing loss (HLS), which led talkers to naturally adopt a clear speaking style. In speech-in-noise listening experiments involving 21 young adult listeners, speech samples by OANH and O AHL were rated and perceived as less intelligible than those of YA talkers. HLS samples were more intelligible than NORM samples, with greater improvements in intelligibility across conditions seen for OA speech. The presence of presbycusis affected (a) the clear speech strategies adopted by O AHL talkers and (b) task effectiveness: O AHL talkers showed some adaptations consistent with an increase in vocal effort, and it took them significantly longer than the YA group to complete the diapix task. The relative energy in the 1–3 kHz frequency region of the long-term average spectrum was the feature that best predicted: (a) the intelligibility of speech samples, and (b) task transaction time in the HLS condition. Overall, our study suggests that spontaneous speech produced by older adults is less intelligible in babble noise, probably due to less energy present in the 1–3 kHz frequency range rich in acoustic cues. Even mild presbycusis in ‘healthy aged’ adults can affect the dynamic adaptations in speech that are beneficial for effective communication.

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## 1. Introduction

The effect of aging and age-related hearing loss (presbycusis) on speech understanding has been investigated in many studies. There has been less attention, however, on the potential effects of aging and presbycusis on aspects of speech production, such as the ability to adapt speaking styles according to prevailing communicative environments. Are older adults as able as younger adults to make ‘clear speech adaptations’ in challenging conditions? Are these

affected by the hearing status of the older adult? Are these adaptations as effective as those of younger adults? These questions were examined in perception studies which used, as materials, naturally-elicited conversational and clear spontaneous speech produced by young and older adults during a problem-solving task. Data from the perception studies, speech acoustic analysis and task duration were then used to investigate whether any acoustic characteristics were strong predictors of intelligibility and communication efficiency.

There is an extensive literature on ‘clear speaking styles’, which talkers naturally adopt in situations in which communication is challenging, either because of an external interference such as noise or other voices, internal auditory interference such as a hearing loss, or because their interlocutor may not share their language or language knowledge (for review, see Smiljanić and

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### Abbreviations

YA:	Young adults
OAHL:	Older adults with hearing loss
OANH:	Older adults with normal hearing
ME1-3 kHz:	Measure of relative energy in the 1–3 kHz frequency region of the long-term average spectrum of speech

Bradlow, 2009; Pichora-Fuller et al., 2010; Mattys et al., 2012; Cooke et al., 2014). Clear speech adaptations have typically been elicited using two different approaches: one involves instructing participants to read sentences in a particular style (e.g. ‘as if to a person with a hearing loss’) and the other involves naturally eliciting clear speech by introducing a barrier to communication. Such natural elicitations are beneficial, as ‘imagined’ interactions may not lead to the same behaviour as actual communication with a conversational partner (e.g., Lam and Tjaden, 2013; Scarborough et al., 2007). Clear speaking styles entail a range of acoustic and linguistic adaptations such as reductions in speaking rates, increases in pause frequency and in fundamental frequency, shifts in the energy distribution in the voice and vowel hyper-articulation (for review, see Cooke et al., 2014). Adaptations are, to a degree, tailored to best counter the interference that the interlocutor may be experiencing (e.g., Cooke and Lu, 2010; Hazan and Baker, 2011). Speaking style adaptations are therefore a fairly skilled aspect of speech production, that are essential for efficient and effective communication in challenging situations.

A recent lifespan study including young and older adults has investigated the acoustic characteristics of their casual and instructed clear speaking styles, among other talker groups and conditions (Smiljanić and Gilbert, 2017a). When asked to read sentences clearly in a quiet environment, older adults reduced their speech rate and produced longer pauses. However, compared to other age groups, they showed less increase in fundamental frequency and in the amount of energy in the mid-frequency region of the long-term spectrum of their speech (1–3 kHz). This finding needs further exploration as instructions to speak clearly may not trigger acoustic adaptations in the older adult group that a more natural mode of eliciting clear speech might.

A few studies have investigated clear speaking style adaptations in older adults by evaluating whether, in listening tests, higher intelligibility is obtained for sentences produced in a clear speaking style than produced in a conversational style (‘clear speech benefit’). In both Schum (1996) and Smiljanić (2013), an examination of clear speech benefit scores for individual YA and OA talkers revealed that, in each group, there were some talkers for whom a substantial clear speech benefit was obtained and others who showed little benefit. However, in a perception study using materials from Smiljanić and Gilbert (2017a), the clear speech produced by all talker groups, including older adults, was shown to be more intelligible when presented in noise than their conversational speech (Smiljanić and Gilbert, 2017b). It is rare for a study to link acoustic analyses of clear speech with a perceptual test of a clear speech benefit so these data are valuable.

As suggested above, evaluating an individual’s clear speech from an analysis of sentences that are read in laboratory conditions provides valuable information but may have limited ecological validity. First, the recorded speech materials are produced without communicative intent and therefore lack the dynamic adjustments that talkers make to their speech in natural interactions, especially when communicating with someone who has difficulty hearing

them. Also, in studies involving read materials by older adults, the older adult is merely a ‘talker’ whereas true communication involves a participant as both listener and talker, and, more often than not, doing another task while communicating. Communicative difficulties, for an older adult, may come not only from their difficulty with understanding their conversational partner, but also because their own voice may be more difficult to understand for others which can lead to mutual breakdowns in communication. It is known, for example, that voicing is weaker in older adults due to greater irregularity in vocal fold vibration and poorer breath control (e.g., Schaeffer et al., 2015). This results in the long-term average spectrum with a greater tilt and thus in having less energy in those areas of the spectrum that are particularly rich in acoustic cue information for phonetic identity. To get a better understanding of communicative difficulties in older adults, it is therefore necessary to investigate ‘speech in interaction’, i.e. not only how intelligible their read speech is but also how they can make themselves understood in conversational interactions in good and adverse communicative environments.

In an effort to better understand how speech changes in the context of spontaneous speech interactions for different types of talkers, research teams have developed new tasks to elicit speech produced with communicative intent but which maintain some control over the lexical content that is elicited. These typically involve two participants completing a problem-solving task; the ease or difficulty of the interaction can be controlled by degrading one or both channels of communication by adding noise, or introducing spectral degradation. The fact that the task involves problem-solving also adds to the cognitive load experienced by the participants and reflects many real-life multi-tasking situations. Such recordings can be used for speech analysis but can also yield measures reflecting communication efficiency. An early example of this approach is the ‘Map Task’ (Anderson et al., 1991) which involved ‘instruction givers’ having to communicate details of a route on a map and its key elements to ‘instruction followers’. Popular problem-solving puzzles such as Sudoku and crosswords have been used to record spontaneous speech in interaction (Cooke and Lu, 2010; Crawford et al., 1994).

A more recent task, which is becoming widely used, is the diapix task (Van Engen et al., 2010). Diapix involves pairs of participants engaged in a ‘spot the difference’ picture task. Each participant is presented with a different version of the same cartoon-style picture, and both have to collaborate to find the differences between the two pictures without seeing each other’s picture. A set of 12 carefully-designed picture-pairs developed by Baker and Hazan (2011) is in the public domain. The differences in the diapix task can be designed to encourage the production of specific words for segmental analyses, although this task is not best suited for phoneme-level analyses as keywords may not be elicited frequently enough for a reliable measure to be made (Baker and Hazan, 2011). This task is more typically used to investigate suprasegmental characteristics of speech, such as speech rate, long-term average spectrum and fundamental frequency measures. Success or communicative efficiency in the diapix task can be assessed using measures such as task transaction time (Van Engen et al., 2010) and frequency of communication breakdowns (McInerney and Walden, 2013). Diapix has been used in studies of clear speech adaptations in young adults (Hazan and Baker, 2011), children with typical hearing (Hazan et al., 2016) and with hearing loss (Granlund et al., 2018), older adults (Tuomainen and Hazan, 2016), native and nonnative talkers (Van Engen et al., 2010). It has also been used to examine how speech characteristics vary when speaking in one’s first and second language (Wester et al., 2014) and phenomena of talker convergence (Kim et al., 2011; Solanki et al., 2015). In clinical settings, a pilot study (McInerney and Walden, 2013) used diapix

interactions to evaluate the effect of assistive listening devices (ALD) on communication efficiency in older adults with hearing loss.

In a recent study, we have used the diapix task to investigate the clear speech adaptations made by large groups of older adults and younger adult controls. In this study, Diapix was carried out in a number of conditions, in which the audio signal received by either the conversational partner alone or for both participants was manipulated to make communication more difficult in order to naturally elicit clear speech adaptations. The ‘elderLUCID’ corpus of recordings that was produced in this study includes speech from 83 talkers: 57 older adults (of which 30 had a hearing loss) and 26 younger adults.

The aim of the phase of the project that is reported in this paper was to examine, for a subset of talkers from the elderLUCID corpus, the relation between speech intelligibility, acoustic characteristics of the speech and communication efficiency. A first research objective was to investigate whether spontaneous speech samples produced by older talkers with typical hearing and with presbycusis were as intelligible, when presented to young adult listeners, as those of younger talkers. Second, we examined, within this talker cohort, what aspects of the talkers’ acoustic profile, if any, were predictors of (a) how efficiently they could carry out the task and (b) how intelligible their speech was, as judged by listeners not involved in the conversation. A subsidiary objective was to compare objective (sentence repetition) and subjective (intelligibility rating) judgments of intelligibility for the same set of items. For both research and clinical purposes, intelligibility ratings are quicker to obtain and score than objective judgments which require participants to repeat or write down sentences heard. It is known that there are strong correlations between these measures for sentences (Speaks et al., 1972; Kollmeier and Wesselkamp, 1997) and spontaneous speech (Cox et al., 1991) produced by young adults. To our knowledge, these correlations between objective and subjective measures of intelligibility have not been investigated for speech of older talkers, although subjective ratings of sentence intelligibility (‘ease of understanding’) in quiet failed to show any age-related differences between YA and OA talkers (Goy et al., 2016). It is possible that due to lower familiarity with older voices, or due to their greater variability, less consistency would be found between objective and subjective judgements made by young listeners for these voices. This comparison is therefore added here.

## 2. Material and methods

### 2.1. Participants

#### 2.1.1. Talkers

The speech corpus used in this study was a subset of the elderLUCID corpus collected by Tuomainen and Hazan. For the current study, a subset of talkers balanced in terms of their age group, sex and hearing status profile was included for both the listening tests and acoustic analyses. 10 talkers (5F) were selected at random for each of three talker groups: young adults (YA), older adults with normal hearing thresholds (OANH) and older adults with age-related hearing loss (OAHL). OANH participants had normal hearing thresholds defined as an average hearing threshold of <20 dB in the better ear across octave frequencies 250–4000 Hz while OAHL participants had a mild acquired hearing loss defined as an average pure-tone hearing threshold of 20–45 dB in the better ear with a symmetrical downward slope in the high-frequency range typical in presbycusis (Table 1). YA participants all had normal thresholds as defined using the same procedure and criteria as the OANH participants. All participants reported no history of speech or language impairments and OA participants were screened for

cognitive impairment using the Mini-Mental State Exam (Folstein et al., 1975).

#### 2.1.2. Listeners

Listeners were 21 young adult (YA) speakers of Southern British English (7F) with a mean age of 25.9 years (s.d. 5.2). They were screened for normal hearing thresholds (<20 dB at octave frequencies .250–4 kHz) and reported that they did not have any hearing or language difficulties.

### 2.2. Speech materials

#### 2.2.1. elderLUCID corpus

The elderLUCID corpus contains spontaneous speech recordings made while participants carried out the diapix task with a conversational partner, a young adult of the same sex. The diapixUK picture pairs developed by Baker and Hazan (2011) were used. During the recordings, the two participants were seated in separate sound-treated booths, without sight of each other, and communicated via microphone headsets. The key participant (talker A) was leading the conversation and was instructed to do most of the talking, whereas their conversational partner (Talker B) was mainly required to ask questions and make suggestions. The young adults recruited in ‘Talker B’ role did not participate in the study in a Talker A role. The pair were instructed to start in the left-hand corner of the picture and work clockwise; they were given 10 min to find the differences.

The recordings from two specific conditions were used for this study: in the NORM condition, Talker A and Talker B could hear each other normally though they could not see each other and were communicating via headphones. In the HLS condition, Talker B could hear Talker A via a real-time hearing loss simulator modeling a profound sensorineural loss at levels 40–50–60–90–90 dB at frequencies 250–500–1000–4000–8000 (HELPS, Zurek and Desloge, 2007). In both conditions, the automated gain control for Talker A’s voice was set for 75 dB SPL up to 8000 Hz, so that talking louder would not lead to a change in intensity for Talker B. The HLS condition severely affected audibility and speech comprehension for Talker B; this required Talker A participants to make adaptations to their speech to maintain effective communication even though they were not directly affected by the interference. Each condition therefore elicited a different speaking style: a conversational style was obtained in NORM, whereas the communication difficulties experienced by Talker B in HLS elicited a clear style in the speech of Talker A. Only the speech of Talker A was used for the listening experiments and acoustic analyses.

#### 2.2.2. Materials used in listening experiments

For the listening experiments, we extracted four short samples for each of the NORM and HLS recordings for each of the 30 talkers. These samples were equally spaced throughout the interaction. Criteria used to select the samples were that they should be self-contained, include 3 to 5 keywords, not include any disfluency and not be produced in response to a clarification request by Talker B. Given the nature of the task, most of these samples were simple descriptions of parts of the pictures with high-frequency lexical items (e.g., ‘the wall is blue, the sheet is white’, ‘there are two goats in the pen’ ‘over the top of the bush is three birds’). Participants in the listening task had no access to the diapix pictures so they had no contextual information. The 240 samples thus selected were normalized for intensity using RMS equalization and mixed with eight-talker babble noise at a signal-to-noise ratio (SNR) of –9 dB.

**Table 1**  
Mean pure tone audiogram thresholds at octave frequencies .250–4 kHz for the OAH, OANH and YA group (N = 10 per group) for the left and right ear. Standard deviations are shown in parentheses and the final column shows the range for the .250–4 kHz average values.

Frequency (kHz)	Left Ear						
	0.25	0.5	1	2	4	.250–4	.250–4 (range)
OAH	17.5 (10.9)	18 (11.4)	20.5 (10.1)	37.5 (14.2)	49.5 (16.4)	28.6 (5.4)	22–40
OANH	7.5 (4.2)	10 (4.1)	12.5 (6.3)	18 (9.2)	26 (13.7)	14.8 (5.1)	5–22
YA	5.5 (6)	4 (6.6)	2 (4.2)	3.5 (5.8)	3.5 (7.1)	3.7 (4.5)	–1–11
Frequency (kHz)	Right Ear						
	0.25	0.5	1	2	4	.250–4	.250–4 (range)
OAH	18 (11.8)	20 (11.1)	24 (13.5)	36.5 (14.9)	49 (16.3)	29.5 (8.6)	20–46
OANH	9.5 (6.9)	9.5 (5.5)	12.5 (9.2)	15.5 (9.3)	24.5 (11.7)	14.3 (6.2)	5–22
YA	5 (6.2)	3 (4.2)	2.5 (4.2)	1.5 (6.3)	2.5 (9.5)	2.9 (4.4)	–4–11

### 2.3. Procedure

Each listener took part in two listening tasks. The repetition task was an intelligibility test that required participants to listen to each sample and repeat what they had heard to the experimenter, who then transcribed the sentence on a laptop computer. From this transcription, the number of keywords correctly produced was calculated. Keywords were counted as correct if repeated verbatim. Repetition switches were counted as correct (e.g., for ‘white shirt and blue trousers’, ‘blue trousers and white shirt’ was correct) but these cases were rare. The second task was an intelligibility rating task; this included the samples by the same talkers that had not been heard, by that participant, in the repetition test. Participants, after hearing each of the randomized excerpts, were required to rate how intelligible each was on a 1 to 7 scale, with 1 described as ‘not very’ (intelligible) and 7 as ‘very’ (intelligible) by clicking a button on a laptop screen.

For both listening tests, samples were presented to listeners via Sennheiser HD437 headphones at a comfortable listening level at 70 dB. The 240 samples were divided into two balanced sets of 120 for each of the two listening experiments. These sets were counterbalanced across participants: a participant only heard each sentence once, but some participants heard a given sentence in the repetition task while others in the rating task.

The data for both tests were organized in two ways. For each listener, mean scores per talker group (YA, OANH, OAH) for each of the NORM and HLS conditions were calculated across all samples produced by the ten talkers in the group. Second, in order to be able to correlate intelligibility scores for individual talkers with their acoustic profile, mean scores were calculated for each talker across 21 listeners for each of the NORM and HLS condition.

## 3. Results

### 3.1. Perception tests

#### 3.1.1. Sentence repetition test

Data for the repetition and rating tests are presented in Fig. 1. For the repetition test (see Fig. 1, left panel), using the data organized per listener, a repeated-measures ANOVA was used to investigate the within-subject effects of talker group (YA, OANH, OAH) and communicative condition (NORM, HLS) on keyword intelligibility rates. There were significant main effects of talker group [ $F(2, 40) = 42.2$ ;  $p < .001$ ;  $\eta^2 = .68$ ] and communicative condition [ $F(1, 20) = 181.11$ ;  $p < .001$ ;  $\eta^2 = .90$ ], and a significant talker group by

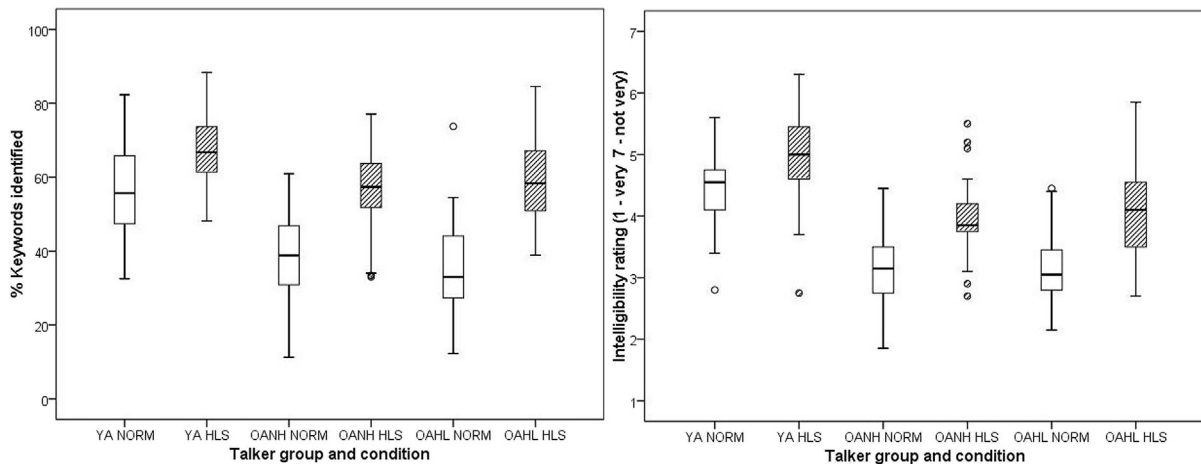
condition interaction [ $F(2, 40) = 9.02$ ;  $p = .001$ ;  $\eta^2 = .31$ ]. Listeners achieved higher intelligibility rates for the YA speech ( $M = 62.6\%$ ) than for OANH ( $M = 46.6$ ) or OAH ( $M = 47.3$ ) speech which did not differ from each other. The effect of condition was due to higher intelligibility scores for the speech produced in the HLS condition ( $M = 60.9$ ) than in the NORM condition ( $M = 43.4$ ) showing evidence of a ‘clear speech’ benefit for speech produced when talkers had to make themselves understood by an interlocutor with a simulated hearing loss. The significant interaction was due to the difference in intelligibility between the NORM and HLS speech differing across the three talker groups: mean absolute difference of 12.1% for YA speech, 17.4% for OANH speech and 22.9% for OAH speech.

In summary, for young adult listeners, OA speech was more difficult to understand than YA speech, but there was a clear speech benefit for all talker groups in the HLS condition, with evidence of greater benefit for the speech produced by OA talkers. As a result, the age-related difference in talker intelligibility was reduced when talkers were producing clear speech adaptations relative to when they were talking in their conversational speech style (difference between YA and OAH mean intelligibility: 20.7% for NORM speech vs 9.8% for HLS speech). The speech of OAH talkers did not differ in intelligibility from that of their peers with normal hearing.

#### 3.1.2. Intelligibility rating test

Next, we examined whether similar effects were obtained when participants had to give intelligibility ratings (see Fig. 1, right panel). For a given listener, these ratings were given for the same set of talkers but for samples not heard in the repetition task. There were significant main effects of talker group [ $F(2, 40) = 107.1$ ;  $p < .001$ ;  $\eta^2 = .84$ ] and communicative condition [ $F(1, 20) = 99.4$ ;  $p < .001$ ;  $\eta^2 = .83$ ], and a significant talker group by condition interaction [ $F(2, 40) = 4.5$ ;  $p = .018$ ;  $\eta^2 = .18$ ]. On a scale of 1 (not very intelligible) to 7 (very intelligible), higher intelligibility ratings were obtained for the YA speech ( $M = 4.7$ ) than for OANH ( $M = 3.6$ ) or OAH ( $M = 3.6$ ) speech, which did not differ from each other. The effect of condition was due to higher ratings being achieved for the HLS speech ( $M = 4.4$ ) than for the NORM speech ( $M = 3.6$ ), which provides evidence of a ‘clear speech’ benefit. The significant interaction was due to the difference in intelligibility ratings between the NORM and HLS differing across groups: 0.6 for YA speech, 0.7 for OANH speech and 1.0 for OAH speech. In summary, very similar effects of talker group and communicative condition were obtained across the repetition and rating data.





**Fig. 1.** Box-plots of repetition task (left panel) and intelligibility rating task (right panel) data for the three talker groups (YA, OANH, OAHL) for spontaneous speech samples from the NORM and HLS conditions of the diapix task. In all cases, the speech samples were presented to young adult listeners in 8-talker babble noise at a fixed SNR of  $-9$  dB.

### 3.1.3. Correlation between sentence repetition and intelligibility rating tests

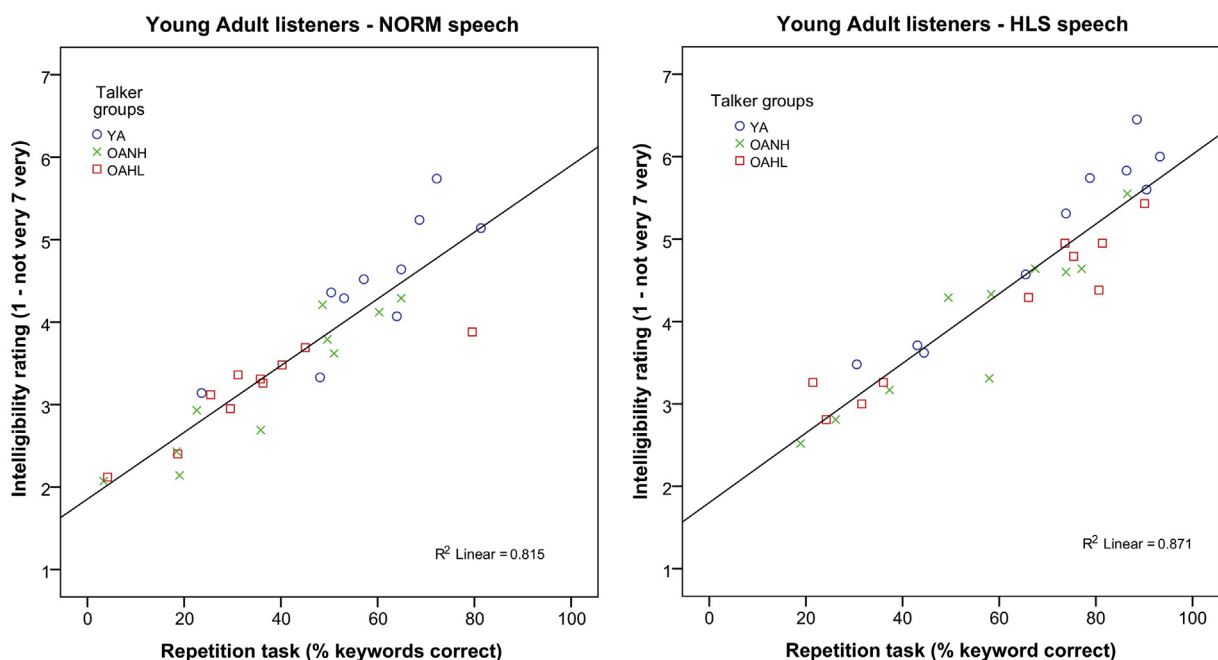
Correlations were assessed using the data organized per talker across all listeners (see Fig. 2). Across all talkers, correlations were significant between repetition and rating scores for NORM speech [ $r(30) = .90$ ,  $p < .001$ ] and for HLS speech [ $r(30) = .93$ ,  $p < .001$ ]. These correlations remained strong when rerun for the data for older adults only:  $r(20) = .90$ ,  $p < .001$  for NORM and  $r(20) = .94$ ,  $p < .001$  for HLS speech. Intelligibility ratings were therefore a good reflection of the actual difficulty in understanding and repeating short spontaneous speech items for older as well as younger voices.

### 3.2. Acoustic profile of talkers' speech

To investigate whether there were any significant predictors of talker intelligibility (see Section 4), an acoustic profile of each individual talker was obtained by carrying out acoustic analyses for

the speech recorded in the NORM and HLS conditions. These acoustic analyses were carried out using the complete diapix recordings rather than the short samples alone, in order to obtain more stable and reliable measures. Analyses included: (a) articulation rate, (b) normalized pause frequency, (c) the relative energy in the 1–3 kHz region of the long-term spectrum (ME1-3 kHz), (d)  $f_0$  median and range and (e) vowel space area. Note that articulation rate is a direct measure of syllable duration, as its calculation excludes pause duration, unlike speech rate. The procedures used for analyzing each of these parameters are described in detail in Hazan et al. (2016) for the duration, energy and  $f_0$  measures and Pettinato et al. (2016) for the vowel space measures. These measures for each of the three talker groups are presented in Tables 2 and 3.

Repeated-measures ANOVAs were run to investigate the within-subject effect of communicative condition (NORM, HLS) and between-subject effect of talker group (YA, OANH, OAHL) on each of



**Fig. 2.** Correlations between the repetition task and intelligibility rating task results for speech samples produced in the NORM (left panel) and HLS (right panel) conditions.

the six measures. For articulation rate, there was an effect of talker group [ $F(2, 27) = 3.4$ ;  $p = .048$ ;  $\eta^2 = .20$ ]; post-hoc analyses showed that YA talkers spoke at a faster rate ( $M = 3.8$ ) than OANH talkers ( $M = 3.3$ ), with OAHL talkers ( $M = 3.6$ ) differing from neither group. There was a main effect of condition [ $F(1, 27) = 20.55$ ;  $p < .001$ ;  $\eta^2 = .43$ ]: HLS speech ( $M = 3.3$ ) was slower than NORM speech ( $M = 3.8$ ). For pause frequency, the only significant effect was that of condition [ $F(1, 27) = 18.4$ ;  $p < .001$ ;  $\eta^2 = .41$ ], with a higher pause frequency for HLS ( $M = .11$ ) than NORM speech ( $M = .08$ ).

For ME1-3 kHz, there was a main effect of talker group [ $F(2, 27) = 4.7$ ;  $p = .018$ ;  $\eta^2 = .26$ ], with a higher ME1-3 kHz in YA group ( $M = 67.1$ ) than the OAHL ( $M = 63.6$ ) and OANH ( $M = 63.9$ ) which did not differ. ME1-3 kHz was higher in HLS ( $M = 65.8$ ) than NORM ( $M = 63.9$ ) [ $F(1, 27) = 37.76$ ;  $p < .001$ ;  $\eta^2 = .58$ ]. The condition by group interaction just failed to reach significance [ $F(2, 27) = 2.9$ ;  $p = .072$ ,  $\eta^2 = .18$ ]: there was a trend for the difference across the NORM and HLS conditions to be smaller for YA speech than both OANH and OAHL speech.

For median f0 (in semitones relative to 1 Hz), the only significant effect was of condition [ $F(1, 27) = 30.4$ ;  $p < .001$ ;  $\eta^2 = .53$ ], with a higher median f0 in HLS ( $M = 89.4$ ) than NORM ( $M = 87.1$ ). For f0 range, there was a main effect of talker group [ $F(2, 27) = 8.2$ ;  $p = .002$ ;  $\eta^2 = .38$ ], with YA talkers having a narrower f0 range ( $M = 3.0$ ) than both OA groups (OANH  $M = 3.9$ , OAHL  $M = 4.1$ ) which did not differ. There was an effect of condition [ $F(1, 27) = 43.5$ ;  $p < .001$ ;  $\eta^2 = .62$ ] with a broader f0 range used in HLS speech ( $M = 3.9$ ) than NORM speech ( $M = 3.4$ ).

Next, we examined evidence for a strategy of increasing vocal effort in HLS, which would be marked by a correlation between an increase in mid-frequency energy (reflecting a decrease in spectral tilt) and an increase in median fundamental frequency in HLS relative to NORM as was found in an investigation of clear speech adaptations in the speech of children (Hazan et al., 2016). A significant correlation was obtained between changes in ME1-3 kHz and changes in median f0 for the OAHL group ( $r = .835$ ,  $N = 10$ ,  $p = .003$ ) but not for the OANH group ( $r = .212$ ,  $N = 10$ ,  $p = .556$ ) or the YA group ( $r = -.094$ ,  $N = 10$ ,  $p = .797$ ).

Finally, for vowel space area, there was an effect of condition [ $F(1, 27) = 7.7$ ;  $p = .010$ ;  $\eta^2 = .22$ ] modified by a condition by group interaction [ $F(2, 27) = 6.0$ ;  $p = .007$ ;  $\eta^2 = .31$ ]. Paired t-tests revealed that this was due to vowel space area increasing in the HLS condition for the YA group only, with no significant change seen for either of the OA groups (see Table 3).

In summary, for this group of 30 talkers, there was clear evidence of acoustic adaptations in speech produced to counter communication difficulties (HLS) and also of some differences in the acoustic profile of YA and OA talkers when clarifying their speech. On average, speech produced in the HLS condition was slower, had more pauses, more energy in the mid-frequency region, a higher f0 and broader f0 range than speech produced in NORM. Certain clear speech features were more prominent in YA speech: YA talkers showed an increase in vowel space not seen in the OA groups, and a trend towards a smaller increase in ME1-3 kHz than older talkers, even though their ME1-3 kHz measure was higher

overall. For this group of 20 OA talkers, the only difference between the speech profile of OANH and OAHL talkers was that only the OAHL group showed evidence of a clear speech strategy consistent with increasing vocal effort (correlated change in median f0 and ME1-3 kHz).

### 3.3. Measure of communication efficiency

A third source of information to use in the regression analyses to be carried out in section 3.4 is a measure of communication efficiency. As the speech that was analyzed was produced in a problem-solving task, a practical measure that reflects how effective the talkers were in communicating with their conversational partner is the time taken to find the first eight differences in the diapix task. Indeed, instances of miscomprehensions and subsequent repairs would lengthen the time needed to complete the task. There were missing data points for 6 talkers (4 OAHL, 1 OANH and 1 YA) who failed to find at least 8 differences in one or both conditions. The effect of condition was significant [ $F(1, 21) = 27.4$ ;  $p < .001$ ;  $\eta^2 = .57$ ]: it took longer for talker pairs to complete the task in the HLS condition ( $M = 5.8$  min) than the NORM condition ( $M = 4.3$ ). The effect of talker group was significant [ $F(2, 21) = 3.8$ ;  $p = .039$ ;  $\eta^2 = .27$ ]: OAHL talkers took significantly longer ( $M = 5.8$ ) than YA ( $M = 4.2$ ) talkers, but OANH ( $M = 5.1$ ) and YA talkers ( $M = 4.2$ ) did not differ. It is also of interest to consider how communication efficiency by the OAHL group in the NORM condition compared with that of the OANH and YA groups when communicating with their conversational partner with simulated hearing loss in HLS. To this aim, a univariate ANOVA was carried out with Time8 as dependent measure for the following talker/conditions: OAHL-NORM, YA-HLS, OANH-HLS. The effect of group was not significant [ $F(2, 23) = 1.509$ ;  $p = .242$ ;  $\eta^2 = .29$ ] suggesting that even without a communication barrier present, the OAHL group took as long to complete the task as when the other two groups were communicating with a conversational partner with a simulated profound loss. Overall, this indicates that the presence of mild presbycusis in the talker leading the problem-solving task had some impact on communication efficiency for talker pairs, even though the OAHL participant was not directly experiencing the communication difficulty affecting their conversational partner.

### 3.4. Regression analysis

In the next phase of the analysis, all three sources of data were used in regression analyses to investigate whether one or more elements of talkers' acoustic profiles were reliable predictors of (a) perceived intelligibility of the talker by independent adult listeners and (b) task efficiency in the HLS condition.

#### 3.4.1. Relation between talker acoustic profile and talker intelligibility

These analyses were first carried out using the sentence repetition scores for the NORM condition per talker ( $n = 30$ ) as dependent variable and the six acoustic measures listed in Tables 2

**Table 2**  
Measure of articulation rate (number of syllables per second), normalized pause frequency and of mean energy in the 1–3 kHz region of the long-term spectrum (in decibels) calculated from recordings of one diapix task per condition per talker. Means and standard deviations are across the 10 talkers for each of the talker groups.

	Articulation rate				Pause frequency				Mean energy (1–3 kHz)			
	NORM		HLS		NORM		HLS		NORM		HLS	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
YA	4.18	0.78	3.45	0.22	0.09	0.04	0.11	0.06	66.66	2.03	67.52	2.95
OANH	3.50	0.47	3.17	0.39	0.07	0.04	0.10	0.04	62.67	3.54	65.22	2.82
OAHL	3.78	0.38	3.43	0.57	0.09	0.03	0.11	0.04	62.38	2.58	64.80	3.44

**Table 3**

Measures of median  $f_0$  and  $f_0$  interquartile range (both in semitones rel 1 Hz) and of vowel space area (in  $\text{ERB}^2$ ) calculated from recordings of one diapix task per condition per talker. Means and standard deviations are across the 10 talkers for each of the talker groups.

	Median $f_0$				$f_0$ range				Vowel space area			
	NORM		HLS		NORM		HLS		NORM		HLS	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
YA	86.74	5.40	88.99	5.29	2.59	0.45	3.34	0.69	17.46	2.34	21.65	3.46
OANH	87.22	3.58	89.02	3.29	3.77	0.82	4.13	0.77	19.53	5.15	20.78	4.8
OAHL	87.44	4.45	90.20	5.18	3.73	0.74	4.39	0.72	18.91	6.73	18.25	5.69

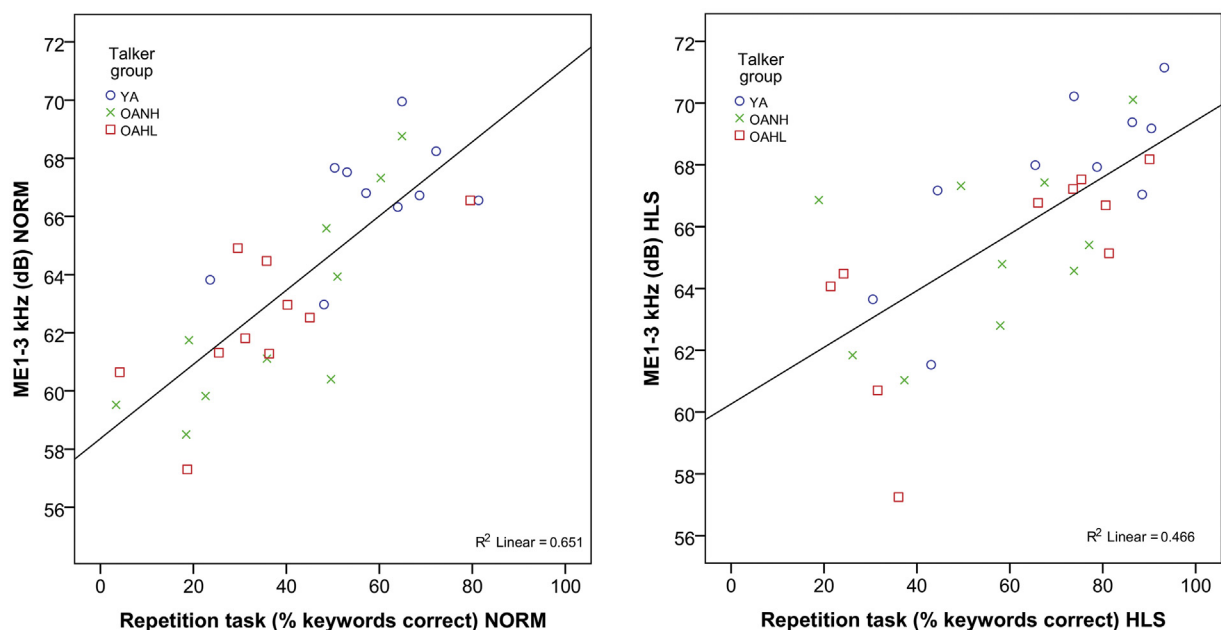
and 3 as independent variables, using stepwise regression. The final model included the ME1–3 kHz measure alone (adjusted  $R^2 = .65$ ), see Fig. 3. When the repetition scores from the HLS condition were used as dependent variable, the final model included ME1–3 kHz and articulation rate (adjusted  $R^2 = .53$ ) with ME1–3 kHz measure accounting for 44.7% of the variance and articulation rate accounting for 8% of the variance. Next, the regression analysis was run on the data for the older adult talkers only ( $n = 20$ ). The model for the NORM condition included ME1–3 kHz as sole predictor (adjusted  $R^2 = .58$ ). For the HLS condition, the final model included ME1–3 kHz and normalized pause frequency (adjusted  $R^2 = .44$ ), with ME1–3 kHz accounting for 35.6% of the variance.

In summary, for the speech produced in both conversational and naturally-elicited clear speaking styles, the relative amount of relative energy present in the mid-frequency region of the long-term spectrum was the only consistent predictor of how intelligible the speech of that talker was when presented in a listening test in background noise. This was the case both for the complete talker cohort or when considering OA speech only. Note also that this was the case even though the lexical content used in the test varied across individual talkers as these were samples of spontaneous speech.

Given the strong correlation between the repetition and rating tasks, one would expect the same predictors to emerge when ratings were used as dependent variable. This was indeed the case. For

the NORM ratings as dependent variable, across all 30 talkers, the final model (adjusted  $R^2 = .71$ ) included ME1–3 kHz ( $R^2 = .67$ ) and pause frequency ( $R^2$  change: .04). When the HLS ratings were used as dependent variable, the final model (adjusted  $R^2 = .59$ ) included ME1–3 kHz ( $R^2 = .52$ ) and median  $f_0$  ( $R^2$  change: .08).

Regression analyses reveal that the ME1–3 kHz measure was predictive of how intelligible a talker was when heard in noise in a laboratory-based listening test but this may not bear any relation to the ease with which these talkers were able to communicate key information to their conversational partner with simulated hearing loss in a problem-solving task. Indeed, there is the possibility that the ME1–3 kHz measure is emerging as a strong predictor mainly due to its impact on the degree to which the babble noise masked the speech in the listening experiment. The task transaction time measure is likely to be affected by many more factors relating to both conversational partners so finding a strong acoustic correlate would be less likely. To investigate this, for the HLS condition, further regression analyses were carried out with the same independent variables, but with the HLS transaction time measure as dependent variable. As above, the final model included ME1–3 kHz (adjusted  $R^2 = .28$ ), see Fig. 4. Although the predictive power of this measure was weaker, it still revealed that the relative amount of energy in the mid-frequency region of Talker A's voice had a predictive effect on how quickly Talker A could complete the diapix task with a conversational partner with a simulated hearing loss.



**Fig. 3.** Correlation between intelligibility rates from the repetition task for NORM (left panel) and HLS (right panel) speech and a measure of mean energy in the 1–3 kHz region (ME1–3 kHz).

#### 4. Discussion

The finding that OA speech was less intelligible to young adult listeners than YA speech when heard in babble noise is in agreement with Smiljanić (2013), even though the two studies differed in the materials used. However, in a recent study involving several age groups, this finding was not replicated (Smiljanić and Gilbert, 2017b) although the difference between YA and OA approached statistical significance. As suggested by Smiljanić and Gilbert (2017b) discrepancies between studies regarding the relative intelligibility of OA speech is at least partly due to the high degree of individual differences in both intelligibility and clear speech benefit across individual talkers.

The fact that a clear speech benefit was obtained for the spontaneous speech of OA talkers confirms findings of studies that used read sentence materials in which talkers were instructed to speak clearly (Schum, 1996; Smiljanić and Gilbert, 2017b). Those instructions might have been expected to lead to more consistent adaptations than would be found in conversational interactions where adaptations change dynamically as a function of the conversational partner's level of understanding and rate of communication breakdowns. Our OA talkers were hearing their 'impaired' interlocutor without interference but still made the necessary adaptations to their speech despite the additional articulatory effort this entailed for themselves; this confirms the relation between articulatory effort and communication ease suggested in Lindblom's Hyper-Hypo model of speech production (Lindblom, 1990).

The adaptations seen in the clear speaking style used by talkers, which were naturally elicited via their interaction with an 'impaired' conversational partner, also mirror those typically seen in studies of 'instructed' clear speech (for a review, see Pichora-Fuller et al., 2010). Indeed, these adaptations included a reduction in articulation rate, an increase in pause frequency, an increase in mid-frequency energy, in median  $f_0$  and in vowel space. However, as shown in Hazan and Baker (2011), the difference between

instructed and naturally-elicited clear speech is likely to be reflected in the extent rather than type of adaptations.

Our study of clear speech adaptations in speech production was the first, to our knowledge, to distinguish OA groups in terms of their hearing status. The adults in our OAH group typically presented with a mild degree of presbycusis. Furthermore, they were healthy and active, as recruited via the 'University of the Third Age' or hiking groups; background questionnaire information revealed that although some owned hearing aids, all but one reported either not using them at all or only using them very occasionally in specific situations. Perhaps unsurprisingly, OAH speech did not differ in intelligibility from that of their peers with normal hearing, and a clear speech benefit was shown for the speech of both groups. Acoustic analyses also revealed few significant differences across the OANH and OAH group, although it appeared that only the OAH group showed a clear speech strategy consistent with an increase in vocal effort, a finding also replicated for the full cohort of talkers in the elderLUCID corpus, which included 27 OANH and 30 OAH participants.

Despite these cross-group similarities, the OANH and OAH groups differed in communication efficiency, with OAH talkers taking significantly longer to complete the diapix task than YA or OANH talkers. The presence of even mild presbycusis therefore affected communication efficiency in this interactive task. In part, this loss of efficiency may have been related to a degradation in the ability of OAH talkers to understand the responses and questions posed by their YA conversational partners in the task. It is also possible that their hearing losses made it more difficult to pick up on subtle acoustic cues their partners provided to indicate that they were struggling to understand the talker's voice in the HLS conditions. Either of these two problems may have been exaggerated by the absence of visual cues in the audio-only interactions used in this experiment. When the same task was carried out in an audiovisual mode with this same talker cohort (Davis et al., 2017), an analysis of the frequency and duration of eye gaze to the conversational partner during the HLS condition revealed that the OAH group produced a similar eye-gaze frequency and duration as YA while OANH talkers produced fewer partner-directed gazes than both other groups (Davis et al., 2017). This supports our hypothesis that OAH participants had a greater need for visual cues than their hearing peers.

Results revealed that the most consistent predictor of both intelligibility and communication efficiency in the task was the amount of relative energy in the mid-frequency region of the long-term average spectrum of speech. This is particularly interesting in light of the fact that the nature of the auditory degradation was very different in these two tasks: the intelligibility measures were obtained in conditions where the talker's voice was mixed with an 8-talker speech babble, and the communication efficiency measures from the task itself when the talker's voice was presented in a condition that simulated a talker speaking in quiet to a listener with a profound hearing loss. Thus, it seems that same strategy of enhancing the energy of the mid-frequency spectrum of speech may provide benefits in a variety of degraded listening situations.

Increases in ME1-3 kHz have also been found in many studies investigating clear speech adaptations (e.g., Krause and Braid, 2009; Hazan and Baker, 2011). A previous study of the acoustic correlates of 'inadvertently clear' speech in young adult and child talkers had also highlighted this measure (Hazan and Markham, 2004), with ME1-3 kHz accounting for 41% of the variance in a word intelligibility in noise task. Spectral flattening has been found to increase intelligibility in noise (Lu and Cooke, 2009). Also, a related measure, spectral balance, i.e. the difference between energy in the low (0–1 kHz) and higher (1–4 kHz) regions of the spectrum, was also found to be the best predictor of perceived listening difficulty for young adult speech (Graetzer et al., 2017).

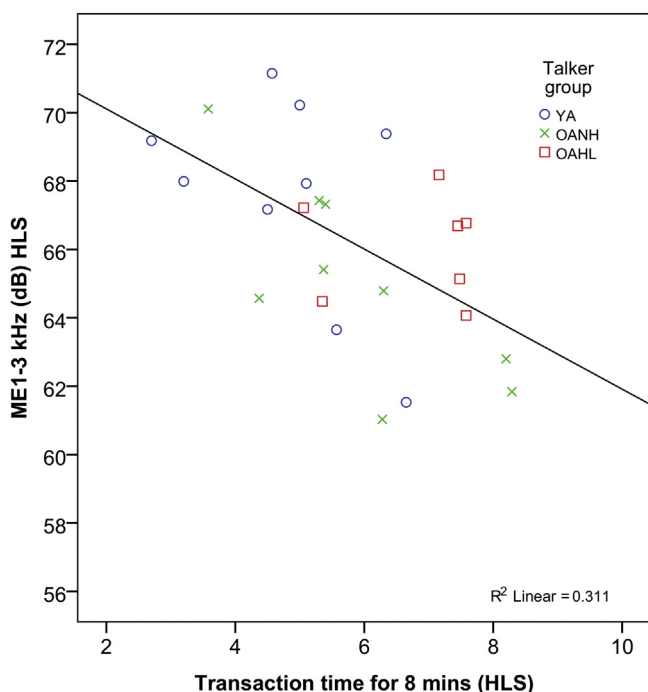


Fig. 4. Correlation between diapix task transaction time in the HLS condition and a measure of mean energy in the 1–3 kHz region (ME1-3 kHz).



Speaking with a 'stronger' voice which results in a reduced spectral tilt therefore appears to yield great benefits in terms of perceived intelligibility. However, this may come at an extra cost for older talkers. It is well known that laryngeal function is affected by aging (e.g. Baker et al., 2001), and changes in laryngeal function can produce a voice with reduced intensity and greater irregularity, which will have a greater spectral tilt (e.g. Schaeffer et al., 2015; Da Silva et al., 2011) and therefore less energy in the mid-frequency spectral region. In a study involving large numbers of talkers, older men were found, in a passage reading task, to speak with lower intensity than younger men (Goy et al., 2013). For older adults, speaking more loudly, which reduces spectral tilt but require greater vocal effort, is likely to lead to greater vocal strain than it would for young adults. The correlation between increases in f0 and increases in ME1–3 kHz that was found exclusively for the OAH group suggests that they particularly made use of this effective but tiring strategy.

In conclusion, it is important to not only consider the impact of presbycusis on speech understanding but also on speech production and communication effectiveness. Automatically enhancing the energy in the mid-frequency range of the speech of older adults could be an effective way of improving communication in challenging conditions.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.heares.2018.06.009>.

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