Linking audiovisual integration to audiovisual speech recognition in noise

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Abstract

Especially in challenging listening conditions, listeners can benefit from the audiovisual nature of speech by using visual information. Yet there exists great inter-individual variability, not only in understanding speech in noise, but also in the benefit obtained from additional visual cues. First empirical evidence suggests that the ability to integrate auditory and visual input, i.e. audiovisual integration, is altered in hearing impairment and is, at the same time, relevant for audiovisual speech intelligibility. The distinct role of mild hearing loss on audiovisual integration and the significance of these changes for speech intelligibility, however, need further scrutiny. Thus, here we investigated differences in audiovisual integration capacities between elderly, normal-hearing and hearing-impaired individuals using two tests of audiovisual integration (sound-induced flash illusion, McGurk task). To explore whether potential differences in audiovisual integration are meaningful for natural speech intelligibility, we then linked audiovisual integration capacities to speech-in-noise recognition using an audiovisual speech-reception threshold test, expecting this to reflect a more realistic listening scenario. Our results indicate that audiovisual integration abilities are already altered in mild hearing impairment, while the magnitude and direction of the effect depend on the specific test used. At the same time, audiovisual integration capacities seem relevant for predicting audiovisual speech intelligibility in noise, especially in those individuals with a hearing loss. We conclude that audiovisual integration abilities should therefore be considered for future predictions of speech recognition outcomes, which – in turn – should be assessed audiovisually, to account for the multisensory nature of speech and communication.

Keywords: flash illusion, McGurk, hearing loss, audiovisual SRT test, multisensory integration

Introduction

Speech intelligibility can be a challenging task with the speed of a conversation reaching up to 200 uttered words per minute [1]. Furthermore, the clarity of the acoustic signal might be compromised – be it due to the characteristics of the speaker (e.g., accent, mumbling), due to the characteristics of the listening situation (e.g., reverberation, background noise), or due to the listener’s impaired hearing abilities. Especially older adults with a hearing loss experience increased difficulties in understanding speech in such challenging listening situations. Therefore, listeners not only rely on the acoustic information, but make use of additional information, such as the linguistic context or visual cues from the speaker’s face. Decades of research have demonstrated that when additional, congruent visual cues are provided, speech recognition is substantially improved for both normal-hearing and hearing-impaired individuals [e.g., 2-10]. This is reflected in an increase of correctly identified audiovisual compared to auditory-only speech [9], improved signal-to-noise ratios (SNRs) [2, 4, 6], accelerated neural speech processing [11, 12], or reduced listening effort for the listener [13]. Thus, integrating auditory and visual information can improve speech intelligibility, especially in noisy conditions in which visual information can provide an increase in the signal-to-noise ratio to as much as 15 dB [2, 4]. This benefit of audiovisual- over auditory-only speech has been termed audiovisual gain or visual enhancement.

While it is well-known that elderly listeners differ greatly in understanding auditory-only speech in noise (SiN), apparently the same is true for audiovisual speech intelligibility and for the extent of using visual speech information. Accordingly, there exists a large variability among individuals in their benefit from additional visual cues, i.e. their audiovisual gain, even when both auditory-only and visual abilities are taken into account [9, 14-17, see also 18]. This might be explained by the finding that listeners differ not only in the extent to which they extract the unisensory signals, but also in the degree to which they combine (or integrate) visual and auditory information [14]. Grant and colleagues described substantial inter-individual differences among hearing-impaired subjects in integrating auditory and visual consonant cues and, importantly, found these to be related to the audiovisual gain, such that those who integrated better also showed a larger audiovisual benefit.

72 These findings and the fact that the variability in SiN recognition has not been fully
73 accounted for by measures of age, auditory- or cognitive abilities [e.g., 19, 20], have
74 prompted the conclusion that audiovisual integration (AVI), i.e. the ability to integrate
75 auditory and visual input, is a distinct capacity, independent of auditory- and visual
76 abilities, and likewise important for audiovisual speech processing [cf. 14, 18, 21, 22].
77 Given the multisensory nature of natural speech and communication [cf. 23], this points
78 to the potential role of audiovisual integration abilities in explaining differences in
79 audiovisual speech intelligibility. At the same time, classical assessments for speech
80 recognition or hearing-aid outcomes apply speech-reception threshold (SRT) tests solely
81 in auditory-only conditions. The undisputable role of visual information for speech-in-
82 noise intelligibility challenges the assumption that auditory-only SRT tests reflect an
83 ecologically valid listening scenario [cf. 24]. Here, we therefore aimed at investigating the
84 relation between audiovisual integration abilities and *audiovisual* speech-in-noise
85 recognition.

86 Different approaches on both neuronal and behavioral levels have been used to
87 measure audiovisual integration [cf. 22, 25]. A common approach is to use paradigms with
88 incongruent audiovisual input that may elicit perceptual illusions necessarily driven by
89 audiovisual integration. Two prominent examples are the McGurk effect [26] and the
90 sound-induced flash illusion (SIFI) [27, 28]. In the prototypical version of the McGurk task,
91 the sound of the syllable /ba/ is presented with the visual image of a speaker articulating
92 /ga/, commonly leading to the fused percept /da/, which is taken as an indicator for AVI.
93 The flash illusion, on the other hand, pairs one flash with multiple beeps, potentially
94 resulting in the illusory percept of multiple flashes, again indicating AVI. Crucially, there
95 exists an individual time interval in which the inputs from the auditory and visual
96 modality are most likely to be integrated, reflected by change in perception or behavior.
97 This time interval is known as *temporal window of integration* or *temporal binding window*
98 (*TBW*), with the latter commonly referring to the stimulus onset asynchronies (SOAs)
99 across which an effect is observed [e.g., 29-32, for review see 33]. Thus, one way to
100 measure the TBW is to vary the SOAs between the stimuli and explore the corresponding
101 perceptual responses.

102 Importantly, the two tests differ not only in the nature of the stimuli used (speech
103 stimuli in McGurk, low-level stimuli in SIFI), but also in the nature of the task and

crossmodal interaction: In the McGurk task, auditory perception might be altered by incongruent visual input, whereas in SIFI, visual perception might be altered by incongruent auditory input. An earlier study found a negative correlation between the two tests in healthy young adults [34]. At the same time, there is converging evidence for distinct neural processes underlying different aspects of audiovisual integration [cf. 35]. Thus, we used both tests to investigate their relationship and their potentially distinct contribution to speech intelligibility in noise

One line of research on multisensory integration in (healthy) elderly adults suggests that they show enhanced audiovisual integration abilities when compared to younger adults [e.g., 36-41], although this has not been found consistently [e.g., 42-44]. Considering the use of various tasks and analysis methods, however, there is good overall agreement on increasing multisensory integration abilities with aging, yet the reasons for these enhanced abilities seem multifactorial [for reviews see 45, 46]. Among others, it is proposed that enhanced integration abilities compensate for unisensory deficits, i.e. for the age-related declines in sensory modalities such as vision and audition. Additionally, although hearing impairment constitutes one of the most prevalent conditions in the elderly, relatively little is known about audiovisual integration in older adults with hearing loss compared to their normal-hearing peers. While there is evidence that AVI alters not only with aging but is also affected by varying degrees of hearing impairment [e.g., 21, 47-49], the separate contribution of hearing impairment to AVI remains to be further explored.

Previous studies have largely focused on cochlear-implant (CI) patients with profound hearing loss [for reviews see 50, 51], whereas studies of rather mild forms of hearing loss and of the effects of hearing aids on AVI have been rare and just recently complemented. Altieri and Hudock [21] revealed relationships between measures of AVI and hearing abilities, suggesting that the ability to integrate auditory and visual speech input is linked to auditory abilities. Adding to this, there is evidence for increased AVI and altered audiovisual speech processing in mild-to-moderately hearing-impaired compared to normal-hearing, older adults, as indicated by the susceptibility to the McGurk effect [49]. A previous study of ours using the flash illusion extended this to hearing-aid use, finding more AVI in hearing-aid users with a mild hearing loss compared to their untreated peers, who were matched for age and degree of hearing loss [52].

In summary, there is evidence for altered AVI abilities in elderly, hearing-impaired listeners and for the potential role of AVI abilities for understanding speech in noise, given the audiovisual nature of everyday-life communication. Nonetheless, the separate role of (mild) hearing loss on AVI and the significance of these changes for speech intelligibility are yet unclear. Thus, here we investigated differences in AVI capacities between elderly, hearing-impaired and age-matched, normal-hearing individuals using two different paradigms, the McGurk task and SIFI. To see whether the potential differences in AVI are meaningful for natural speech intelligibility, we then linked AVI capacities to SiN recognition using an audiovisual SRT test [53], arguing that this reflects a more realistic listening scenario.

This study was motivated by three main topics. We aimed at investigating (i) AVI capacities, (ii) audiovisual SiN recognition and the audiovisual gain, and (iii) the relation between AVI and audiovisual SiN recognition in elderly, hearing-impaired (HI) individuals and age-matched, normal-hearing (NH) controls. To that end, we compared those two groups across two tests of AVI (McGurk, SIFI) with respect to their susceptibility to the respective illusion and the corresponding temporal binding window, as well as in their performance in an audiovisual SRT test. Finally, we linked these measures by means of a stepwise linear regression to evaluate the amount of (additional) predictive value of AVI for SiN intelligibility, beyond the influences of age and hearing abilities.

We formulated the following three hypotheses:

H1) We predict that groups would differ in their AVI abilities as indicated by the McGurk and SIFI, with more McGurk illusions in the HI compared to the NH group and the opposite for SIFI, that is, more illusory flashes in the NH group than the HI group.

H2) We predicted that the HI individuals perform worse in the audiovisual SRT test than NH individuals but possibly display a larger audiovisual gain.

H3) Finally, we assume that AVI abilities would account for additional variance in audiovisual SiN recognition particularly in the HI group and for the McGurk task, which is more speech-like than the flash illusion.

Materials and Methods

Participants

Twenty-five normal-hearing individuals (NH) with a mean age of 68.8 ± 5.3 years, and twenty-five hearing-impaired individuals (HI) with a mean age of 70.4 ± 6.2 years, participated in this study. The age did not differ significantly between the groups [$T_{(48)} = -0.929$, $p = 0.357$]. The hearing-impaired group displayed a mild, symmetric, and age-related hearing loss (presbycusis) that was typically present in the high frequencies. According to the WHO definition, they had better-ear pure-tone averages across the frequencies 0.5, 1, 2, and 4 kHz (PTA-4) of between 26 and 40 dB HL [cf. 54, 55] with a mean PTA-4 of 31.3 ± 7.7 dB HL, whereas the normal-hearing group had PTA-4 values below 20 dB HL (mean PTA-4 of 9.2 ± 3.0 dB HL), with PTA-4 differences between left and right ear smaller than 15 dB HL and air-bone gaps no larger than 10 dB HL. **Fig 1** shows the individuals' pure tone audiograms averaged over both ears. None of the subjects reported prior hearing-aid experience.

Fig 1: Pure-tone audiograms of the participants. Shown are the individual pure-tone audiograms for normal-hearing (left) and hearing-impaired (right) participants (mean across both ears) as well as group averages (dashed line).

All participants had normal or corrected-to-normal vision and did not show indication of dementia (age-normed DemTect scores of > 8) [56]. The groups did not differ in the DemTect scores [$T_{(48)} = -0.877$, $p = 0.385$]. Individuals with psychiatric or

neurological disorders were excluded from the study. The study was approved by the local ethics committee of the University of Oldenburg (Committee for Research Impact Assessment and Ethics) and performed in accordance with the Declaration of Helsinki. All participants gave their written, informed consent prior to the study and received a monetary compensation for participation.

Tests and stimuli

To assess audiovisual integration (AVI) capacity as well as the corresponding temporal binding window, the test battery comprised two tests, the *McGurk-MacDonald illusion* (*McGurk*) and the *sound-induced flash illusion* (*SIFI*), with the individuals' susceptibility to the respective illusion taken as an indicator for the strength of AVI and the time frame in which the illusions occurred as an indicator for the respective TBW. To determine speech-in-noise intelligibility for auditory-only and audiovisual conditions, we used the *Audiovisual Oldenburg Sentence Test* (*AV-OLSA*).

Tests of audiovisual integration

McGurk

In the McGurk task, participants saw video clips of a speaker's face and heard spoken syllables, which were either congruent to the lip movement of the speaker or incongruent, which may result in auditory illusions when indicating the syllable heard [26].

As audiovisual stimuli, a subset of syllables by a male speaker, created in the Department of Media Production at the University of Oldenburg, was used [49]. Specifically, we only used the syllables /da/ and /ba/, commonly resulting in the illusory fusion percept /da/ when presented in an incongruent condition (i.e. visual /gav/ paired with auditory /ba_A/), as previous studies found this combination to be the most robust in eliciting the McGurk illusion in healthy, German-speaking participants [49, 57].

The test consisted of seven conditions: Four unimodal conditions involving auditory-only (*A_{only}*) /ba_A/ and /ga_A/ as well as visual-only (*V_{only}*) /bav/ and /gav/ with five repetitions each, two audiovisual congruent (*AV_{cong}*) conditions (/ba_A-bav/, /ga_V-gav/) as well as the incongruent, illusory fusion condition (*AV_{incong}*) /ba_A-gav/. The auditory and visual stimuli were presented either synchronously (SOA of 0 ms) or across SOAs of 70–420 ms in steps of 50 ms to quantify the temporal binding window, with the onset of the

tone following the onset of the video. Each SOA (0, 70, 120, 170, 220, 270, 320, 370, 420 ms) was repeated ten times, summing up to 200 interleaved trials in total for the whole test, which lasted approximately 20 minutes.

For this task, the participants were instructed to report what they perceived aurally or - in case of visual-only conditions - what they perceived visually (i.e. could read from the lips). Prior to each trial's stimulus presentation, a 1000 ms blank screen was presented followed by a jittering 600–800 ms black fixation cross on white background. After each trial, the three syllables (/ba/, /ga/, /da/) were displayed as response options (labeled 1, 2, 3), from which the answer had to be chosen and the respective number reported to the experimenter (three-alternative forced choice). As in SIFI, the next trial only started after the experimenter had entered the response.

Prior to the experiment, the intensity of the auditory stimulus delivered via headphones was set individually to the comfortable loudness level of each participant, which was adjusted in steps of 1 dB until it was judged as easily audible and medium loud, starting at 65 dB SPL. The mean medium loudness level of the auditory stimuli in the normal-hearing group was 66.9 ± 2.6 dB SPL compared to 68.5 ± 2.6 dB SPL in the hearing-impaired group.

Sound-induced flash illusion (SIFI)

In SIFI, visual flashes are paired with either a congruent or an incongruent number of auditory beeps, which may result in visual illusions when instructed to indicate the number of flashes perceived [27, 28].

Stimuli and set-up were similar to and described in more detail in [52], except for carrying out two runs of the test per participant, once with 0.5 kHz beeps and once with 2 kHz beeps in randomized order. We used these frequencies to investigate whether a low- versus a high frequency would affect the number of illusory perceptions, especially in the hearing-impaired group, whose hearing loss was characteristically present in the high-frequency range.

Each of the two runs consisted of seven conditions: Four unimodal conditions (one flash *1F*, two flashes *2F*, one beep *1B*, two beeps *2B*) as well as three bimodal conditions, which comprised two congruent ones (one flash paired with one beep *1F1B*, two flashes paired with two beeps *2F2B*) and the incongruent, illusory (or so-called fission) condition

where one flash was paired with two beeps (*1F2B*). Unimodal and bimodal congruent conditions served as controls, while the incongruent one was used to quantify the strength of audiovisual integration in SIFI.

To determine the temporal binding window, eight stimulus onset asynchronies (SOAs: 70, 120, 170, 220, 270, 320, 370, 420 ms) between the flashes and beeps were tested in conditions with multiple flashes or multiple beeps, with the first flash always starting simultaneously with the first beep. In the incongruent fission condition (*1F2B*), the second beep was always presented after the flash-beep pair. Each SOA was repeated ten times in bimodal (*1F2B*, *2F2B*) and five times in unimodal (*2F*, *2B*) conditions. Conditions without SOAs (*1F*, *1B*, *1F1B*) involved ten repetitions, resulting in 270 randomized trials in total for each run (0.5 kHz, 2 kHz). One run lasted about 15 minutes and was preceded by a short training session.

The participants were instructed to report the number of flashes they perceived and to ignore the beeps. Each trial started with a white fixation cross, centered on a black background, which the participants had to fixate throughout the whole trial. After 1000 ms, the first flash was presented. After each trial, the subjects were asked to indicate the number of flashes to the experimenter, who entered the response before the next trial started. The two unimodal auditory control conditions (*1B*, *2B*) were tested in an immediately following, separate block, as in that case the instruction was to report the number of beeps heard.

As in the McGurk task, auditory stimuli were presented via headphones and the loudness adjusted analogously in steps of 1 dB to medium loudness for each participant prior the test and training session, starting at 70 dB SPL for the respective beep. The mean loudness level set in the normal-hearing group was 68.8 ± 3.7 dB SPL for the 500 Hz beep and 69.4 ± 3.8 dB SPL for 2 kHz, and 70.9 ± 3.5 dB SPL and 71.5 ± 3.9 dB SPL, respectively, in the hearing-impaired group.

Audiovisual speech intelligibility-in-noise task

Audiovisual Oldenburg Sentence Test (AV-OLSA)

One aim of the study was to link audiovisual integration capacities to audiovisual speech intelligibility in noise. Therefore, we used a newly developed audiovisual speech

reception threshold (SRT) test: the Audiovisual Oldenburg Sentence Test (AV-OLSA) [53, *see also* 58, 59].

The AV-OLSA is based on the auditory-only female Oldenburg Sentence Test (Oldenburger Satztest, OLSA), a well-validated auditory SRT test with high precision [60-63]. Llorach and colleagues developed a corresponding audiovisual version by recording video material with the original female speaker and “dubbing” that onto the original, validated auditory stimulus material. Just like the OLSA, the AV-OLSA is a matrix test using sentences of the form “name-verb-numeral-adjective-noun”, with the array of words being a random combination from an inventory of 50 words.

In the AV-OLSA, participants heard these five-word sentences in background noise and simultaneously saw the speaker’s head including her lip movement. After each trial, they repeated what they heard and the speech level then changed adaptively to obtain 80% SRTs. In the auditory-only (AO) condition, the auditory sentences were presented with a black screen.

We tested auditory-only (AO) and audiovisual (AV) conditions of 20 sentences each in fluctuating background noise (ICRA4-250). The ICRA4-250 originates from the ICRA4 noise of the International Collegium for Rehabilitative Audiology, that is a female, speech-modulated, and fluctuating noise [64]. In the ICRA4-250 noise, the maximum ‘speech pauses’ in that noise were limited to 250ms (Wagener et al., 2006). While the presentation of the conditions was randomized, the preceding training with ten sentences each had a fixed order (AO, AV). The sentences were automatically chosen based on the previously tested lists, to avoid repetition.

In this experiment, we applied an open response format, i.e. after each sentence, the participant repeated all the words he or she has understood to the experimenter and was not given visual response alternatives like in a closed format. For each condition, the corresponding 80%-SRTS were determined, referring to the signal-to-noise ratio (SNR) that yields 80% intelligibility based on word scoring. To obtain the threshold, an adaptive procedure [cf. 65] was applied; with a fixed background noise presentation level at 65 dB SPL and the target speech adaptively varying based on the previous answer, starting at 0 dB SNR.

Experimental procedure

The study comprised three tests – SIFI, McGurk, AV-OLSA – performed in random order across participants. SIFI and McGurk took place in a light- and sound-attenuated cabin, where participants were seated approximately 60 cm in front of the screen. The experimenter sat perpendicular to the set-up and, after each response, made the data entry on a keyboard. In both tests, visual stimuli were presented on a 17” Iiyama ProLite T 1731 SR-B1 monitor with a spatial resolution of 1280 × 1024 pixels and a luminance of 200 cd/m² at a refresh rate of 60 Hz. Sound stimuli were presented via Sennheiser HDA200 headphones delivered by the USB audio interface RME Fireface UC (http://www.rme-audio.de/en/products/fireface_uc.php). Stimulus presentation was controlled by Presentation® software (Version 18.2, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) run on an ASUS P8 Z77V computer equipped with an Intel Core i7 950 processor and an ATI Radeon HD 5700 graphics card. Prior measurements with an optical sensor and audio software confirmed synchronicity between the visual and auditory stimuli and the correct timing of SOAs.

The AV-OLSA was completed in a sound-attenuated, quasi free-field room with the experimenter sitting laterally facing the participant with a different screen for making the data entry after each response. The loudspeaker (Genelec 8030A), delivering both speech and noise, was placed approximately 175 cm ahead in front of the participant (S₀N₀). The visual stimuli were presented on a 22” View Sonic TD 2220 Full HD monitor with a spatial resolution of 1920 x 1018 pixels, approximately 60 cm in front of the participant. Sound stimuli were delivered by the USB audio interface RME Fireface. The experiment was run on an ASUS Prime B250-PRO computer, equipped with an I5 3.2 GHz processor (generation 6), 16 GB RAM, and an on-board Intel HD S30 graphic card. Stimulus presentation was controlled by Matlab with the use of the VLC player for sentence and picture presentation, and Soundmex for background noise.

Data analysis

Tests of audiovisual integration

For both SIFI and McGurk, we first calculated each participant’s proportion of correct responses for each condition and SOA, as well as the proportion of illusory reports for

each SOA in the respective incongruent, illusory conditions, i.e. $1F2B$ for SIFI and AV_{incong} for the McGurk task. Additionally, the mean values across SOAs were obtained for each individual.

Potential group differences between normal-hearing (NH) and hearing-impaired (HI) individuals were tested by means of repeated-measures general linear models (GLM), with Greenhouse-Geisser correction when the assumption of sphericity was violated. In those cases, adjusted p values are reported and the deviation from sphericity indicated by epsilon (GG_{eps}). To maintain a significance level of 0.05 in multiple pairwise comparisons or t tests, Bonferroni correction was applied, and adjusted p values are indicated.

McGurk

In a first analysis, we investigated the control conditions (A_{only} , V_{only} , mean AV_{cong} across SOAs) using a repeated-measures GLM on the proportion of correctly identified syllables with condition as within-subject factor (using the mean value across SOAs) and group (NH, HI) as between-subject factor.

The incongruent condition AV_{incong} was analyzed separately to investigate possible group differences in the degree of susceptibility to the McGurk effect (defined as fusion reports /da/) for each of the nine SOAs (0–420 ms). Therefore, we first assessed the fusion reports by a repeated-measures GLM with SOA as within- and group as between-subject factor. In AV_{incong} , responses can be classified as the auditory percept /ba/, the visual percept /ga/, or the (illusory) fusion percept /da/, indicating an integration of the visual and auditory syllable. To examine the response behavior in more detail, the respective response proportions across SOAs were submitted to a repeated-measures GLM with group as between-subject factor and response to the incongruent /baA-gav/ condition (/ba/, /ga/, /da/) as within-subject factor.

In addition, we wanted to quantify the temporal binding window for the McGurk task following a similar approach as in SIFI [cf. 52, 66]. When analyzing the fusion response to the incongruent AV_{incong} condition, it should be kept in mind that some of those fusion responses could be attributed to errors in the percept of the unimodal components (i.e. auditory or visual percept) instead of reflecting true bimodal perception. Especially visual-only conditions can be prone to errors. Assume that a participant with a fusion response (/da_{AV}/) of 60% for audiovisual, incongruent /baA-gav/ conditions might also

perceive a visual /gav/ as /dav/ in 20% of the cases (visual error) and an auditory /ba_A/ as /da_A/ in 3% of the cases (auditory error). These unimodal error rates have to be taken into account to determine the number of “truly” audiovisually fused illusion responses [cf. 30, 34]. Hence, analogously to SIFI, we compared the proportion of fusion responses in AV_{incong} to the proportion of visual and auditory errors in /gav/ and /ba_A/ trials, respectively, using Bonferroni-corrected paired-sample *t* tests. The contiguous span of successive SOAs in which the fusion proportion was significantly higher than the combined error proportion then determined the temporal limits of the window of integration for the McGurk task [cf. 52, 66].

SIFI

As in the McGurk task, we first investigated proportion of correct responses in the control conditions (1F, 2F, 1B, 2B, 1F1B, 2F2B) of each frequency by a repeated-measures GLM with frequency and condition as within-subject factors (using the mean value across SOAs) and group (NH, HI) as between-subject factor.

Secondly, we probed whether the groups showed an overall susceptibility to the illusion by accounting for errors in the congruent condition. To that end, we compared the proportion of illusory responses (i.e. more than one flash) in the incongruent fission condition (1F2B) to the congruent control condition (1F1B), again using a repeated-measures GLM for each frequency with condition (mean across SOAs) and group (NH, HI) as within- and between-subject factor, respectively.

For the investigation of potential group differences in the amount of illusion across SOAs, a repeated-measures GLM on the proportion of illusory responses in the 1F2B condition for each SOA was applied, with SOA (70–420) and frequency (0.5 kHz, 2 kHz) as within- as well as group (NH, HI) as between-subject factor.

Finally, to determine the temporal binding window in SIFI for each group, the same approach as in [52] was applied, that is, the temporal limit of the illusion was defined as the contiguous span of consecutive SOAs in the 1F2B condition in which the proportion of illusory reports was significantly higher than in the 1F1B control condition, as determined by Bonferroni-corrected paired-sample *t* tests [cf. 66]. This was carried out for each frequency separately.

Correlation SIFI and McGurk

To investigate the relationship between the two tests in each group, we calculated Pearson's correlation scores between the mean fusion responses in the McGurk and the mean illusory responses in SIFI (mean across SOAs and frequencies) for both the HI and NH groups.

Test of audiovisual speech intelligibility in noise (AV-OLSA)

From the AV-OLSA, we obtained one 80%-SRT value for both auditory-only (AO) and audiovisual (AV) condition, referred to as AO-SRT₈₀ and AV-SRT₈₀. To assess the audiovisual gain, we further calculated the difference between both intelligibility scores, i.e. AV-SRT₈₀ – AO-SRT₈₀.

Relation of audiovisual integration and audiovisual speech intelligibility in noise

Finally, we linked audiovisual integration to audiovisual speech-in-noise recognition. As we were interested in whether, and to what extent, audiovisual integration capacities can explain variability in audiovisual speech intelligibility in noise beyond age and hearing abilities, we performed a stepwise linear regression for each group with *AV-SRT₈₀* as outcome variable and *Age*, *PTA-4*, *Mean % SIFI illusion* (mean across SOAs and mean across frequencies due to correlation), as well as *Mean % McGurk illusion* (mean across SOAs) as potential predictor variables.

The stepwise approach used both an inclusion and removal criterion for variable selection. At each step of the regression, one variable of the set of potential predictor variables that has not yet been entered and has the smallest probability of F is added into the regression equation if that probability is sufficiently small (0.05). Simultaneously, variables already in the equation are eliminated if their F probability becomes sufficiently large (0.10). The approach stops at a model where no more variables are suitable for inclusion or removal.

All statistical analyses were performed with IBM SPSS Statistics for Windows, version 24.0.

Results

Tests of audiovisual integration

McGurk

We first investigated the control conditions (A_{only} , V_{only} , mean AV_{cong} across SOAs) to compare the correct identification of syllables between groups (see **Fig 2**). While the main effect of condition was found to be significant [$F_{(2,96)}=72.73$, $p_{adj}<0.001$, $GG_{eps}=0.62$, $\eta^2_p=0.60$], the main effect of group was not [$F_{(1,48)}=2.24$, $p=0.141$]. Post-hoc comparisons did not show a significant improvement from auditory-only to audiovisual congruent conditions across both groups [$d_{AV-A}=2.2$, $T_{(49)}=1.61$, $p_{adj}=0.114$]. The benefit from both audiovisual and auditory-only presentation over visual-only conditions, however, was significant [$d_{AV-V}=27.0$, $T_{(49)}=9.82$, $p_{adj}<0.001$; $d_{A-V}=24.8$, $T_{(49)}=7.18$, $p_{adj}<0.001$].

Fig 2: Mean percent correct responses (across SOAs) in each control condition (V_{only} , A_{only} , AV_{cong}) for the normal-hearing (NH, dark grey) and hearing-impaired (HI, striped) groups. Asterisks indicate significant differences between conditions (both $p_{adj}<0.001$) in post-hoc comparisons (mean across groups) following a significant main effect of condition in the corresponding ANOVA ($p_{adj}<0.001$).

To investigate potential group differences in the susceptibility to the McGurk effect, the proportion of fusion reports (/da/) in the audiovisual incongruent condition AV_{incong} were analyzed for each SOA, exposing a significant main effect of group with a large effect size [$F_{(1,48)}=18.35$, $p_{adj}<0.001$, $\eta^2_p=0.23$]. Overall across all SOAs, HI individuals showed a higher number of fusion reports and thus, a higher susceptibility to the McGurk effect, than normal-hearing individuals ($42 \pm 30\%$ vs. $11 \pm 20\%$), consistent with hypothesis H1. Both main effect of SOA and SOA $\times$ group interaction likewise yielded significance [SOA: $F_{(8,384)}=14.96$, $p_{adj}<0.001$, $\eta^2_p=0.24$; interaction: $F_{(8,384)}=4.38$, $p_{adj}=0.002$, $\eta^2_p=0.08$] with decreasing illusory reports with increasing SOAs in the HI group.

Since in AV_{incong} conditions participants could either report the illusory fusion percept /da/ by integrating both presented syllables, or respond in line with the auditory (/ba/) or the visual (/ga/) component, we examined the response behavior in more detail. This resulted in a significant main effect of response [$F_{(2,96)}=50.44$, $p_{adj}<0.001$, $\eta^2_p=0.51$], but also a significant response $\times$ group interaction [$F_{(2,96)}=19.80$, $p_{adj}<0.001$, $\eta^2_p=0.29$]. Post-hoc analysis revealed that across all SOAs, HI individuals reported the fusion percept significantly more often than NH individuals [$42 \pm 30\%$ vs. $11 \pm 20\%$, $d_{HI-NH}=30.7$, $T_{(48)}=4.28$, $p_{adj}<0.001$], whereas NH answered more frequently in line with the auditory component of the presentation, i.e. gave the ‘correct’ response /ba/, compared to HI [$86 \pm 25\%$ vs. $45 \pm 33\%$, $d_{HI-NH}=-40.5$, $T_{(48)}=-4.89$, $p_{adj}<0.001$]. At the same time, HI also responded more often in line with the visual component (/ga/), i.e. showed a higher visual bias than NH [$13 \pm 19\%$ vs. $3 \pm 6\%$, $d_{HI-NH}=9.79$, $T_{(48)}=2.48$, $p_{adj}=0.017$]. **Fig 3** shows the response behavior for the two groups across SOAs.

Fig 3: Response rate across SOAs in the incongruent audiovisual /ba_A-ga_V/ condition (AV_{incong}) of the McGurk task for the normal-hearing (NH, left panel) and hearing-impaired (HI, right panel) group. Possible responses were the auditorily-driven percept [ba], the visually-driven percept [ga] or the fusion percept [da] indicating integration of the auditory and visual syllable. The shaded area reflects the window of integration for the HI group. NH individuals relied largely on the auditory percept, whereas the HI group reported significantly more illusory fusion responses. HI individuals were most likely to integrate visual and auditory syllables in asynchronies up to 170 ms between the lip movement and the spoken syllable. With increasing SOAs, the rate of fusion responses decreased, while the auditory response rate increased, intersecting at 170 ms.

Furthermore, we aimed at obtaining the temporal binding window for the McGurk task in each group, accounting for unisensory visual and auditory errors in the audiovisual fusion percept. Comparing the illusory /da/ reports in the incongruent condition to /da/ reports in visual-only /ga_V/ and auditory-only /ba_A/ trials (error proportions) for each SOA resulted in significant 'true' fusion percepts ranging from 0 to 170 ms in the HI group (all $p_{adj} < 0.05$), while the temporal window could not be determined for NH not showing the illusion. The window coincides with the intercept, where the number of auditorily-driven responses exceeds the number of fusion responses (**Fig 3**).

Put differently, hearing-impaired individuals were more likely than NH to experience an audiovisual illusion in an auditory task, with the highest probability of illusory

percepts in asynchronies up to 170 ms between the lip movement and the spoken syllable. Outside of this window of 170 ms, they responded more in line with the ‘correct’ auditory percept. However, some individuals of the HI group also relied on the visual percept. The NH individuals were significantly less prone to the McGurk illusion, but responded in line with the correct auditory component. Compared to the NH group, the HI group showed significantly more fusion responses across all SOAs. Furthermore, across both groups, increasing hearing loss was associated with increased audiovisual integration and reduced auditory bias.

SIFI

The analysis of the control conditions (*1F*, *2F*, *1B*, *2B*, *1F1B*, *2F2B*) across both frequencies (0.5 kHz, 2 kHz) and between the two groups (NH, HI) exposed a significant main effect of condition [$F_{(5,235)}=82.59$, $p_{adj}<0.001$, $GG_{eps}=0.54$, $\eta^2_p=0.64$]. At the same time, neither the main effect of group nor the main effect of frequency yielded significance, with $F_{(1,48)}=0.222$, $p=0.64$ and $F_{(1,48)}=0.001$, $p=0.98$, respectively. Likewise, none of the two-way or three-way interactions between condition, frequency, and group were significant, indicating that the performance of both groups was similar across the control conditions, independent of the frequency. To follow up on the main effect of condition, post-hoc multiple comparisons were performed and revealed that conditions with a single flash/beep (*1F*, *1B*, *1F1B*) did not differ from each other, but did significantly differ from conditions with multiple flashes/beeps (*2F*, *2B*, *2F2B*), which in turn also significantly differed amongst each other (all $p_{adj}<0.05$). For both frequencies, both NH and HI experienced a benefit from congruent bimodal presentations (*2F2B*) as compared to the unimodal visual condition (*2F*), but performed best in the unimodal auditory *2B* condition (across all SOAs).

To test whether groups showed an overall susceptibility to the illusion, we compared the proportion of multiple-flash reports in the incongruent illusory *1F2B* condition (collapsed across SOAs) to the *1F1B* control condition. While significantly more illusory reports were observed in the incongruent than in the control condition [main effect of condition $F_{(1,48)}=22.5$, $p<.001$, $\eta^2_p=0.32$], groups did not differ significantly from each other [main effect of group $F_{(1,48)}=0.009$, $p=0.925$]. Apparently, both NH and HI individuals experienced the illusion similarly when averaging across SOAs, with no notable group differences, thus not supporting H1.

To further analyze the susceptibility to the flash illusion in the *1F2B* condition in more detail by taking into account the varying SOAs, the number of illusory reports for each SOA was analyzed. Here, we found an expected significant main effect of SOA [$F_{(7,329)}=29.38$, $p_{adj}<0.001$, $GG_{eps}=0.71$, $\eta^2_p=0.39$], with post-hoc tests confirming decreasing numbers of illusion with increasing SOAs. Again, the main effect of group was not significant [$F_{(1,48)}=0.011$, $p=0.915$], nor was the main effect of frequency [$F_{(1,48)}=0.125$, $p=0.725$], or any of the interactions between SOA, frequency, and group. This suggests that NH and HI did not differ from each other in their illusory reports, but both experienced fewer illusions with increasing SOAs, similarly in both frequencies (0.5 kHz, 2 kHz). A paired sample *t* test conducted groupwise between the frequencies for each SOA revealed no significant intra-group difference between the frequencies when corrected for multiple comparisons.

Finally, to determine the frequency-specific temporal binding window for each group, we applied the approach by Foss-Feig and colleagues [52, 66]. For the 0.5 kHz beep, we found that both NH and HI groups showed significantly higher illusory reports in the *1F2B* compared to the *1F1B* condition successively across SOAs of 70–120 ms (all $p_{adj}<0.05$), which defines the temporal limits of the integration window. In the 2 kHz run, HI individuals showed the same window of integration (–120 ms), whereas the NH group’s window was extended by one SOA (–170 ms) (all $p_{adj}<0.05$). These results, as shown in **Fig 4**, indicate a slightly broader window in NH, but only for the high-frequency tone.

Fig 4: Percent of illusion in the incongruent *1F2B* condition of SIFI. Shown are the ‘two flashes’ reports across SOAs for the normal-hearing (NH, solid lines) and hearing-

impaired (HI, dashed lines) group in the 0.5 kHz run (left) and the 2 kHz run (right). The shaded areas show the respective temporal binding window for each group.

Correlation between SIFI and McGurk

To investigate the relationship between the two tests, we calculated correlation scores, but did not find a significant relationship in either group [HI: $r=-0.110$, $p=.599$; NH: $r=-0.023$, $p=0.913$].

Test of audiovisual speech intelligibility in noise (AV-OLSA)

To test speech-in-noise intelligibility, we applied the audiovisual SRT test AV-OLSA, obtaining 80%-SRTs in fluctuating background noise for the auditory-only (AO) and audiovisual (AV) conditions. **Fig 5** shows the boxplots for each condition as well as the gain from adding visual information, defined as SRT difference between AV and AO conditions. As hypothesized in H2, normal-hearing individuals showed significantly lower, i.e. better SRTs in both the AO condition compared to the HI group [-8.3 dB SNR ± 2.1 vs. -0.8 dB SNR ± 4.1 , $d_{\text{NH-HI}}=-7.5$ dB, $T_{(48)}=-8.12$, $p_{\text{adj}}<0.001$] and in the AV condition [-15.4 dB SNR ± 4.9 vs. -7.5 dB SNR ± 3.7 , $d_{\text{NH-HI}}=-7.9$ dB, $T_{(48)}=-6.41$, $p_{\text{adj}}<0.001$]. This means that the signal-to-noise ratio could be much lower for NH individuals in order to understand ~80% of the words.

Contrary to H2, however, the gain from adding visual information was almost equal in both groups, with -7.1 dB ± 4.2 for NH and -6.7 dB ± 3.3 for HI participants [$d_{\text{NH-HI}}=-0.4$ dB, $T_{(48)}=-0.34$, $p=0.74$]. Apparently, both groups benefitted equally from adding visual information. Note, however, the larger variability among the NH participants in the AV condition and in the gain.

Fig 5: 80%-SRTs for auditory-only (AO, left) and audiovisual (AV, middle) conditions as well as the gain (AV-AO, right) for the normal-hearing (NH, dark grey) and hearing-impaired (HI, light grey) participants. The speech-reception thresholds indicate the signal-to-noise ratios where ~80% of the speech is understood. NH individuals showed lower, i.e. better, SRTs than in both auditory-only and audiovisual conditions, whereas the gain obtained from additional visual information was almost equal in both groups.

Relation of audiovisual integration and audiovisual speech recognition in noise

In the last step, we linked audiovisual integration capacities, as determined by the susceptibility to the flash- and McGurk illusion, to audiovisual speech-in-noise intelligibility, to explore whether, and how much variance in audiovisual SiN recognition (AV-SRT₈₀) can be explained by AV integration variables – beyond age and hearing loss.

To that end, a stepwise linear regression was performed on the AV-SRT₈₀ with *Age*, *PTA-4*, *Mean % SIFI illusion* (across both frequencies) and *Mean % McGurk illusion* as predictor variables.

Table 1 shows the final model for each group with the selected variables in respective order of selection, as well as the change in variance explained (adjusted R^2). For NH participants, *Age* and *McGurk illusion* account together for 29% overall variance in

audiovisual speech intelligibility, of which 12% is explained by the *McGurk illusion*. In HI individuals, more overall variance of speech intelligibility is explained (60%) by *PTA-4* and both tests of AV integration (*SIFI*, *McGurk*), with the latter accounting for 25.5%. The signs of the beta coefficients indicate that those with more McGurk illusions and fewer SIFI illusions have better (i.e. lower) audiovisual SRTs. Overall, these results support hypothesis H3.

Table 1: Prediction of audiovisual speech intelligibility (AV-SRT₈₀) by age, hearing loss, and tests of audiovisual integration for normal-hearing (NH) and hearing-impaired (HI) participants.

Group	Step	Predictor included	Beta	p	R ²	R ² _{adj}	R ² _{adj} change
NH	1	Age	.642	.004	.207	.171	
	2	Mean % McGurk illusion	-.423	.042	.352	.290	.119
HI	1	PTA-4	.678	.000	.372	.345	
	2	Mean % Flash illusion	.420	.004	.564	.525	.180
	3	Mean % McGurk illusion	-.305	.034	.650	.600	.075

Shown are the predictors entering the final model of the stepwise linear regression for predicting AV speech intelligibility (80%-SRT in AV conditions) with the corresponding beta coefficients as well as the order of variable selection. Furthermore, the corresponding change (ΔR^2_{adj}) in the amount of the adjusted coefficient of determination (R^2_{adj}) is presented, reflecting the proportion of explained variance by adding the predictor to the regression model.

Discussion

In this study, we investigated the influence of age-related, untreated, mild hearing impairment on audiovisual integration capacities and linked those for the first time to audiovisual speech-in-noise recognition to evaluate the amount of (additional) predictive value beyond age and hearing loss.

We hypothesized that hearing loss would exert an influence on audiovisual processing such that H1) groups would differ in their AVI capacities, and H2) groups

would differ in the audiovisual SiN recognition as well as in the gain obtained from visual information. Moreover, we probed H3) whether, and to what extent, audiovisual SiN intelligibility can be predicted by measures of AVI, expecting this to be particularly the case for the HI group and the McGurk task using speech stimuli.

With regard to hypothesis H1), results indicated that groups differed in their AVI capacities and the corresponding window of integration, yet only indicated by the McGurk illusion with HI participants showing increased audiovisual integration compared to the NH group. As to hypothesis H2), the HI group showed expectedly worse SRTs in audio-only and audiovisual SiN conditions, yet did not differ from NH in their audiovisual gain. Concerning hypothesis H3), AVI capacities indeed accounted for additional variability in audiovisual SiN recognition beyond age and hearing loss, especially in the HI group.

Audiovisual integration capacities

McGurk

The McGurk illusion is an established paradigm to assess audiovisual integration on a behavioral level [26, 67]. In contrast to SIFI using low-level stimuli, the McGurk illusion uses speech syllables and can thus be regarded as a gauge particularly for audiovisual *speech* integration. Aiming at assessing the influence of mild hearing loss on these measures, we compared the strength of AV speech integration capacities between NH and HI participants using the susceptibility to the illusion as an indicator.

As hypothesized, elderly HI individuals were significantly more prone to the McGurk illusion, indicating greater AV speech integration capacities compared to their NH peers. The effect of mild hearing impairment on AVI was evident across all SOAs ranging from 0 ms (synchronous presentation) up to 420 ms, with the auditory stimulus presentation lagging the visual one, as groups differed significantly across all ranges. Compared to the HI group, the NH individuals showed less AV speech integration and responded most often in line with the (correct) auditory component. At the same time, both fusion and (correct) auditory responses correlated positively and negatively, respectively, with the degree of hearing loss.

While numerous previous studies have focused on the influence of (healthy) aging on multisensory integration abilities [e.g., 36-40, 42-44, 68, 69, for reviews see 45, 46], the

results on effects of age-related hearing impairment on AVI are comparatively scarce, especially for mild-to-moderate hearing loss. This is aggravated by the fact that studies use different tests and measures of AVI, which might yield different results; this emphasizes the importance of interpreting results in a task-specific context [cf. 70].

We found only two studies comparing AVI capacities by means of the McGurk illusion in untreated mild-to-moderate hearing loss. First, our findings replicated results of Rosemann and Thiel [49], who found enhanced AVI capacities in mild-to-moderately HI compared to NH individuals as indicated by McGurk fusion percepts, and who likewise reported a significant correlation between response behavior and hearing loss. Note that we also used a subset of their stimuli. Similarly, our results are in line with those of Stropahl and Debener [71], who investigated mild-to-moderately hearing impaired and normal-hearing subjects as well as cochlear-implant (CI) patients. They reported increased McGurk illusions in the HI compared to the NH group, with the latter more frequently choosing the auditory response, whereas the CI patients did not display significantly higher illusion rates compared to NH, but rather responded in line with the visual component of the McGurk condition.

We extended those findings by additionally varying the SOAs, thus assessing the corresponding temporal window of (speech) integration, i.e. the time frame in which auditory and visual speech syllables are most likely to be integrated while at the same time reflecting a true bimodal response rather than unimodal errors [cf. 30]. While for the NH group, the window could not be determined with our approach due to overall low fusion reports, the HI group experienced expectedly fewer illusions with increasing SOAs and showed a temporal window of speech integration up to 170 ms, with auditory information lagging visual. Thus, when auditory and visual speech stimuli were presented within this window, the probability of AV speech integration for hearing-impaired individuals was highest. With increasing temporal disparities beyond that window, the HI group was rather driven by their auditory perception. Some individuals, however, also relied on the visual percept.

Some studies have investigated the influence of temporal disparity between the stimuli in the McGurk effect in (younger) healthy adults [e.g., 30, 72, 73], consensually suggesting the illusion to be relatively robust against higher latencies of the auditory information. Although our results seem to match those of Van Wassenhove [30] and

Munhall and colleagues [73], reporting significant fusion responses up to +170 ms and +180 ms (audio lag), respectively, we cannot directly compare the window, as they measured undergraduate students and used a different approach to determine the limits of the window. At the same time, the window width depends on the task, stimuli, individual factors, training, and approaches of quantification [e.g., 31, 34, 74-77]. Thus, numerically, we can only compare our two groups suggesting that untreated hearing-impaired individuals are more likely to integrate even asynchronous audiovisual speech than their normal-hearing peers in an auditory task.

Although our groups did not differ in the visual-only condition, the HI group showed a small but significantly higher bias for the visual component in the incongruent McGurk condition compared to NH individuals. This resembles the pattern in Stropahl and Debener's study [71], although it was not reported by Rosemann and Thiel [49]. Other studies using the McGurk illusion in CI patients have similarly found them to show a bias towards visual information, presumably by placing more weight on the visual modality due to their degraded auditory modality [e.g., 71, 78-82, for review see 51].

Taken together, these findings can be interpreted in the light of theories that put forward a weighting of information and modalities according to their reliability, which in turn affects audiovisual integration [e.g., 83-85, for review see 86]. Accordingly, the more reliable modality dominates audiovisual processing and overall perception. CI users with profound hearing loss and hearing-impaired individuals without hearing aids experience degraded auditory input, therefore they might place more weight on the visual modality (relative to NH individuals) in an auditory task such as the McGurk. Hence, they either integrate auditory and visual information more, as indexed by higher fusion reports compared to NH listeners (this study, [49, 71], and/or display a higher bias towards the visual component.

Summing up, our results for the McGurk task indicate that even mild, untreated hearing impairment affects audiovisual speech integration, with increasing hearing loss being associated with increased integration in an auditory task. At the same time, it extends previous findings, in that we found the window of speech integration to comprise ~ 170 ms for HI listeners.

SIFI

In contrast to the McGurk task, we did not find group differences in the strength of audiovisual integration as indexed by the susceptibility to the flash illusion, for neither low nor high frequency. This was contrary to our expectations of overall higher illusory reports in the NH group. In line with the above-stated model of cue weighting according to reliability, we hypothesized that the HI individuals would place more relative weight on the visual modality and thus experience fewer visual illusions. At the same time, we wanted to probe a possible interaction effect of frequency, as it was conceivable that HI experience more illusions in the 0.5 kHz conditions, as this resembles a frequency range which should not be affected by the age-related, high-frequency loss. Unexpectedly, we found that HI and NH individuals were equally prone to the visual illusion across SOAs from 0 to 120 ms, with neither inter-group nor intra-group differences for the frequency. The only difference was found for the window size in the 2 kHz run, where NH individuals showed a slightly broader window comprising 170 ms.

Previous studies using the flash illusion with varying SOAs have reported temporal windows up to 150 ms in young, healthy adults [28, 69, 87], compared to a greater susceptibility along with broader windows (up to SOAs of 400 ms) in elderly, normal-hearing adults [69, 87, 88]. In contrast, investigations in older adults with hearing impairment using the flash illusion were nonexistent and just recently complemented by a study of ours, in which we found differences between mildly hearing-impaired hearing-aid users in contrast to those with the same degree of hearing loss who had not yet been treated with hearing aids [52]. There, we found greater audiovisual integration together with a wider window of integration for the treated compared to the untreated group of HI subjects, with the former displaying an integration window of 370 ms compared to 220 ms in the latter. We put those results in perspective with other studies and argued that both hearing impairment and hearing-aid use may affect audiovisual integration, speculating that the possibly adverse effects of hearing loss on audiovisual integration (as indexed by SIFI) might be reversed by hearing-aid use. To shed light on the separate effects of hearing loss and hearing-aid use, we stressed the need for a normal-hearing control group, which we wanted to complement with this study.

Although the untreated group of our previous study was comparable to our current HI group with respect to age and hearing loss, and we used the same SOAs as well as the

approach to window quantification [66], we did not obtain exactly the same window size for the HI group, but a narrower one in this study. This might be due to (a) an overall lower susceptibility in the current cohort compared to the old data (mean % illusion across SOAs 14% vs. 18%) with a lower onset of susceptibility reports in the shortest SOA of 70 ms (39% vs. 44%), and (b) an apparently sharper drop in illusion reports in the current group in SOAs of up to 170 ms, compared to the less sloping curve in the group of the previous study. The differences in results might be explained by the overall intra- and inter-individual variability in the perception of the flash illusion [89, 90].

While we cannot conclusively explain the discrepancy between the previous and current data for the untreated HI group, the actual comparison of interest here is between the groups of untreated HI and NH individuals. We were interested in whether a mild hearing loss would have an influence – independent from hearing-aid use – on audiovisual integration in a visual task having an incongruent auditory input. We assumed NH individuals to be more prone to the illusion, as they may place more weight on their intact, reliable auditory modality relative to HI individuals and are thus, more influenced by the incongruent number of beeps [cf. 52]. In contrast, we expected the HI individuals to show a shift towards reliance on the visual modality, being less influenced by their degraded auditory modality. This would have been indicated by more correct and fewer reports of illusions in the HI compared to the NH group, and possibly also an interaction in the sense that for the higher frequency this might be more apparent than in the unaffected low frequency range. However, our current data does not support these hypotheses.

In contrast to the McGurk effect, SIFI represents a task requiring better temporal discrimination abilities, which in turn is a key determinant for the weighting process determining whether signals are integrated [34]. While the precision of temporal processing abilities decline with age [38, 87, 91-94, for review see 45] and older adults show a shift towards visual dominance, recent work indicates that the relation between temporal processing and perceptual multisensory integration becomes decoupled in (healthy) aging [70, 95, for review see 96]. Importantly, Fitzgibbons and Gordon-Salant [93] found the impaired temporal acuity in older compared to younger adults to be independent of hearing loss. Thus, compromised temporal processing, as also reflected by a broader temporal binding window [34, 70, 76, 87, 97], might become apparent as an effect of aging but not as a direct effect of (mild) age-related hearing loss.

The finding that both HI and NH individuals weighted the auditory modality equally in a visual task requiring temporal discrimination supports the concept that the overall superior temporal discrimination ability of audition persists in mild hearing loss (or has been recalibrated). Compared to the hearing-aid users of our previous study, however, both show decreased illusion reports indicating that they still rely more on the visual modality relative to hearing-aid users.

Summing up, both HI and NH participants are equally likely to integrate low-level audiovisual input in a visual task within a window of 120 (or 170 ms, respectively), when the auditory information lags the visual. Group differences in the strength were not observed, thus not giving evidence for a separate effect of a mild hearing loss on audiovisual integration abilities for an auditory-modulated visual task requiring temporal processing with low-level stimuli.

Relation between SIFI and McGurk

We expected the direction of potential differences in audiovisual integration between the groups to be dependent on the specific test of audiovisual integration, yet did not detect a significant correlation between the two tests for either group.

Although both are classical paradigms for assessing audiovisual integration on a behavioral level, they are fundamentally different. In SIFI, visual perception is affected by incongruent auditory information, whereas in McGurk, auditory perception is altered by incongruent visual information. Moreover, SIFI uses low-level stimuli, whereas the McGurk task uses speech syllables. Despite these task differences, Stevenson and colleagues [34] found both to be negatively correlated in younger adults. Hence, those with more McGurk illusions showed a lower susceptibility to the flash illusion and vice versa. These findings are not supported by our results, indicating that the tests might reflect two different aspects of audiovisual processing. Support for this notion also comes from a study by Tremblay et al. [98], who used both tests in a developmental study in children, reporting the strength of audiovisual speech integration to vary with increasing development, whereas the non-speech illusion remained stable across ages.

A previous study has put forward the idea of – at least partly – different mechanisms underlying integration effects of speech compared to non-speech material [99], supported by electrophysiological studies [100-102]. A review by Calvert [35] concluded that

distinct crossmodal interactions also involve distinct brain areas that are differently involved in multisensory integration processes [see also 103]. She also underlined the dependence of the specific experimental paradigm used, the kind of stimuli/information to be integrated, as well as the specific modalities taxed. This is echoed by the finding that older listeners apparently show an intact integration ability of speech stimuli at a phoneme-level, but show compromised integration of whole words [104].

This might also explain supposedly inconsistent findings e.g., in aging-related multisensory integration research [for reviews see [45, 46, 96] and stresses the importance of interpreting results of audiovisual integration at a task-specific level, in contrast to deriving generalizations from one specific paradigm.

Audiovisual speech-in-noise recognition

When measuring speech recognition in noise, our expectations were confirmed in that normal-hearing listeners had better SRTs in both auditory-only and audiovisual conditions compared to hearing-impaired listeners. Likewise expectedly, both groups showed an audiovisual benefit over the auditory-only condition. At the same time, both groups displayed the same amount of visual gain as defined by the difference between the AO and AV condition. Hence, the groups benefitted equally from additional visual information.

It is well documented that providing additional visual- beyond auditory information, and corresponding integration of these, improves speech intelligibility, especially in adverse listening conditions such as noise [e.g., 2, 5-8, 10, 23, 105, 106]. A benefit from audiovisual compared to auditory-only presentations of sentences has, inter alia, been shown for CI patients [e.g., 107] and mildly hearing-impaired listeners [e.g., 14], but also for normal-hearing listeners [e.g., 2]. Our findings add to previous ones similarly reporting a poorer performance of HI listeners compared to NH listeners in both auditory-only and audiovisual conditions [108, 109].

When it comes to the relative use of visual information by HI and NH individuals, results are mixed: Some studies found hearing-impaired individuals to be more sensitive to visual phonetic information in visual speech perception and to display higher speech-reading abilities [110, 111] and to make more use of the visual modality compared to NH

adults [112-115], whereas others did not find differences in lip-reading abilities [9, 116]. While one could expect HI individuals to display a higher audiovisual gain compared to NH listeners [cf. 117], our result echoes the findings by Tye-Murray et al. [9], who likewise reported no significant differences in the visual or auditory enhancement between NH and HI listeners, neither on consonant -, word -, nor sentence level. Correspondingly, Rosemann and Thiel [49] found a similar audiovisual benefit for their NH and HI subjects in an audiovisual sentence task.

As the auditory component likely remains the primary source in audiovisual speech recognition, not only for normal hearing [118] but also in hearing impairment [119-121], audiovisual speech intelligibility of HI individuals should likewise decrease with degraded auditory input compared to NH listeners – yet, only when constant or fixed SNRs or SPLs are used [cf. 108, 109]. Moradi and colleagues [122] assume that if SNRs or SPLs are individually set, as in Tye-Murray’s [9] or Rosemann and Thiel’s study [49], the difference in AV speech recognition between NH and HI listeners would cancel out. We similarly used adaptive SNRs, obtaining the individual’s signal-to-noise ratio where 80% of the speech was understood, which might explain the equal audiovisual benefit for the two groups.

On a related note, results of a study by Puschmann et al. [48] point towards the possibility that changes in audiovisual processing in hearing-impaired individuals may only appear for incongruent, conflicting information from the auditory and visual modality rather than for congruent audiovisual input. This might also clarify why we found differences between NH and HI individuals in the McGurk test using incongruent audiovisual speech stimuli, but not in the AV-SRT test presenting congruent audiovisual speech information.

Lastly, measurements in terms of SRTs do not reflect the effort a listener uses to obtain that SRT [cf. 123-125]. It is possible that our groups do not exhibit a numerical difference in the audiovisual gain but differ in the amount of listening effort.

Summing up, we found that both HI and NH individuals showed an AV benefit over AO conditions, which is in line with the broad literature on the AV gain, although groups did not differ in their gain from the additional visual information.

Relation of audiovisual integration and audiovisual SiN recognition

Despite the evidence for altered audiovisual processing in elderly adults with hearing impairment, the perceptual effects, e.g., for speech recognition, had previously not been adequately examined. In a last step, we therefore linked audiovisual integration capacities, as determined by the susceptibility to the flash- and McGurk illusion, to audiovisual speech intelligibility in noise, to explore whether and to what extent, variance in AV SiN recognition can be explained by variables of AV integration – beyond age and hearing loss.

The stepwise regression revealed group differences: In the NH group, only one third of the overall variance in AV speech intelligibility was explained by age and audiovisual integration (McGurk). In contrast, more overall variance was explained for the HI group, not only by hearing loss but also by both measures of AVI, which accounted for almost half of the overall variance. Specifically, those with fewer flash illusions and more McGurk illusions had lower AV SRTs and thus better audiovisual speech-in-noise recognition at less favorable SNRs.

A plethora of studies has investigated the differential role of various factors in speech-in-noise prediction. Recapitulating, age and hearing thresholds have been reliably identified as good predictors across various studies [20, 126-129, for review see 19]. Simultaneously, however, it became apparent that those measures fail to comprehensively explain the variance in speech recognition, especially in hearing-impaired listeners and under adverse listening conditions such as in noise. Houtgast and Festen [20] emphasized that the hitherto investigated measures of auditory and cognitive abilities still fail to comprehensively account for the variability in SiN recognition, with about 30 % missing. Hence, not all factors crucial for speech-in-noise recognition had been investigated up to that point.

We aimed at filling that gap by investigating the influence of audiovisual integration capacities on specifically audiovisual speech intelligibility in noise, given the multisensory nature of speech and the fact that listeners vary in their usage of visual speech information [9, 14, 16]. We found that AVI abilities account for additional variance in AV speech-in-noise recognition, especially for hearing-impaired individuals. So far, no study has

investigated the influence of two tests of audiovisual integration on audiovisual SiN intelligibility. Grant and Seitz [15] linked the McGurk effect to the audiovisual benefit for consonants and sentences in participants with mild-to severe hearing loss, reporting a positive correlation, whereas in their regression model, the susceptibility to the McGurk effect was not selected as predictor variable for the audiovisual benefit. Van Engen and colleagues [130] added to this by investigating the effect of AV integration, as indexed by the McGurk effect, to audiovisual sentence recognition (comparable to our outcome measure), likewise not finding a relationship and therefore arguing that the McGurk effect may not reflect a valid and relevant measure for audiovisual speech processing. While at first glance their findings seem to contradict ours, they investigated young, normal-hearing individuals. It is conceivable, that the influence of AVI abilities on AV speech-in-noise intelligibility only emerges when unisensory abilities are compromised as in aging in general and in hearing impairment in particular. This might also explain why the predictive value of both tests of AVI is larger in our HI group than in our NH group.

At the same time, it should be emphasized that in the NH group, only the McGurk tests emerged as significant predictor, whereas in the HI group, the susceptibility to the flash illusion was selected before the McGurk susceptibility. Given that both tests were not correlated, they seem to contribute independently to speech-in-noise recognition, which is also supported by the fact that the coefficients of tests were opposite. Taken together, these results again underline the previous statement that the two tests of audiovisual integration might reflect two distinct aspects of audiovisual processing and can rather complement each other rather than being used interchangeably.

Limitations

Some limitations of this study should be pointed out, such as the observational character of the study. Although our groups were closely matched in terms of age and were screened for cognitive abilities, we cannot rule out that they differed in another systematic way besides hearing loss, e.g., in specific cognitive domains. Furthermore, we focused on a group with mild hearing impairment, wherefore our results cannot be generalized to more severe forms of hearing loss nor to treated hearing loss (with CIs or hearing aids). Although we aimed at assessing the influence of hearing impairment, a younger control group would have helped to separate age effects that might have added

to the equivocal findings in multisensory integration research. Furthermore, the high variability of the NH group in the AV gain and in the AV condition, being only partly explained by our included measures, points towards other factors that are particularly important in normal-hearing individuals for audiovisual SiN recognition, such as, for example, cognitive abilities. At the same time, it remains to be elucidated what underlies the variability in AVI abilities. The use of a different frequency in the flash illusion complicates a direct comparison between our previous (Gieseler et al., 2018) and the current study. Furthermore, in the McGurk task, we used a three-alternative forced choice approach, while some argue that one should include at least one open-choice set, e.g., ‘other’, as the response restriction might lead to a biased response distribution [131].

Conclusion

Our results provide evidence that audiovisual integration abilities are already altered in mild hearing impairment, while the exact direction depends on the specific test used. This suggests that different measures of AVI reflect different integration processes and should thus not be used interchangeably. At the same time, we found that AVI abilities are relevant for audiovisual speech intelligibility in noise, especially for individuals with a hearing loss. We thus conclude that AVI abilities should be considered for future predictions of speech recognition and hearing-aid outcomes, which – in turn – should be measured audiovisually to account for the multisensory nature of speech and communication, and improve the ecological validity. The finding that AVI abilities are related to SiN intelligibility moreover prompts the idea that training of AVI abilities may improve speech intelligibility under challenging listening conditions.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Compliance with Ethical Standard section

Approval for the study was obtained from the Research Ethics Committee of the University of Oldenburg (no 25/2018) and the study was carried out in accordance with the ethical standards of with the Declaration of Helsinki. All participants gave their written informed consent prior to the study.

Author Contributions

AG, MT, and HC formulated the overall research question; AG conceptualized the specific research question. AG, MT, SR, CT, KW, and HC contributed to the study design and experimental set-up. AG carried out the experiments together with the Hörzentrum Oldenburg GmbH under the responsibility of KW. AG analyzed the data and wrote the manuscript. MT, SR, CT, KW, and HC critically reviewed and significantly contributed to the manuscript.

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