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Quantifying Miscommunications in Triadic Conversations: Effects of Hearing Impairment, Hearing Aids, and Background Noise

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ABSTRACT

Background: Conversations are an important part of our social lives, although for people with hearing impairment (HI), conversations can pose a considerable challenge and can often lead to miscommunications.

Design: In conversations recorded from 25 groups consisting of one HI interlocutor and two normal hearing (NH) interlocutors, all miscommunications were identified to evaluate how HI, background noise level, and hearing-aid signal processing affected miscommunications. A subset of miscommunications is so-called other-initiated repairs (OIRs) where one interlocutor signals a communication breakdown, using unspecific open requests (e.g., "What?") or increasingly more specific restricted requests or offers (e.g., "Who?" or "Did you say blue?"). An "open request" signals a problem without specifying what is misheard/understood, while the restricted request specifies what part of the sentence is not heard, and finally, the most specific "restricted offer" is asking the conversation partner to confirm the supposed word/phrase. With increasing communication difficulty, open OIRs are expected to be more frequently used due to poorer speech understanding.

Results: The results showed that HI interlocutors generally had more miscommunications and that, across interlocutors, open OIRs were mostly used. At low noise levels, the HI interlocutor had fewer miscommunications and used more specific OIRs when wearing a hearing aid relative to being unaided. At the high noise level, all interlocutors had more miscommunications. When listening to directional sound processing (dir) at the high noise level, the HI interlocutor produced fewer open OIRs. It is interesting that the NH interlocutors were also affected by having more miscommunications and more open OIRs when the HI interlocutor listened to dir. The speech levels of the HI interlocutors were reduced in dir, and a relationship was found between the HI speech levels and the number of OIRs made by the NH interlocutors.

Conclusions: Our results highlight how sensitive the number and nature of miscommunications and OIRs in conversations are, not only to the sound environment, but also to the experience of a single (HI) interlocutor, even in triadic interactions, where only two interlocutors are strictly needed to keep the conversation going.

Key words: Conversation, Hearing impaired, Hearing loss, Other-initiated repairs.

Abbreviations: DIR = directional sound processing; FTO = floor-transfer offset; HA = hearing aid; HI = hearing impaired; NH = normal hearing; OIR = other-initiated repair; Omni = omnidirectional sound processing; PTA4 = pure-tone average across 0.5, 1, 2, and 4 kHz.

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INTRODUCTION

Communication between people is an important and integral part of our everyday lives. However, for people suffering from impaired hearing (HI), conversations can pose a considerable challenge and are a key reason for people to seek hearing-aid treatment (Meyer et al. 2011). Indeed, in hearing-aid users have reported that the most important situations to hear well in are conversations in noise, with family at home, and in small groups (Dobyan & Kihm 2025).

Research has consistently reported that hearing impairment (i) reduces social participation (Huang et al. 2024), (ii) increases anxiety (Hogan et al. 2015), (iii) increases emotional fatigue (Holman et al. 2019), and (iv) lessens their experienced life quality (Ciorba et al. 2012). Their frequent difficulties hearing and having to ask for conversation partners to repeat themselves increase the risk of being perceived as socially and cognitively impaired (Southall et al. 2010). To avoid this, HI interlocutors might revert to strategies of monologuing (Stephens & Zhao 1996), to avoid listening, or to completely withdraw from the conversation and/or the situations in which the conversations occur (Stephens et al. 1999). The latter can consequently lead to loneliness and depression (Shukla et al. 2020).

In their most basic form, conversations consist of an exchange of turns between conversation partners (interlocutors), which are meant to create mutual understanding between them. If a person misses essential parts of conversational speech, for example, due to HI, there is a breakdown in the mutual understanding between conversation partners, and the person is left unable to follow/understand the ongoing conversation. In the following, communication breakdowns will be denoted "miscommunications," which have previously been defined as speech that non-deliberately causes disagreements between interlocutors in the interpretation or understanding of what is said (Linell 1995). To resolve a miscommunication, an interlocutor can disrupt the conversational flow to ask for clarification of the problematic speech (trouble source) (Schegloff et al. 1977), thereby instigating a so-called "other-initiated repair" (OIR) in which interlocutors in the conversation jointly resolve the miscommunication. Beyond OIRs, non-OIR miscommunications also include (i) letting the misunderstanding pass, (ii) providing nonverbal signals of misunderstanding through body language or facial expressions, (iii) repeating due to misalignment of turn-taking (Miles et al. 2023), and (iv) instances of not answering a question or clearly answering wrong.

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OIRs are generally resolved following a certain sequence: (1) A conversation partner instigates an OIR by signaling that they experience a miscommunication, and (2) the speaker of the trouble source tries to fix/solve the miscommunication (repair solution). (3) This can immediately resolve the miscommunication with (4) a repair confirmation (the acknowledgment that the miscommunication was resolved), after which the conversation can resume. Note that it is possible for the first two steps to be repeated with additional repair turns if the initial repair solution is insufficient (Schegloff et al. 1977; Lind et al. 2004).

Focusing on the formulation of verbal OIRs (step 1 above), there are generally three types of repair initiators which have different levels of specificity: Open requests, restricted requests, and restricted offers (Dingemanse et al. 2015). Open requests, such as "what?,' "sorry?," "huh?," or "I did not hear that," signal an unspecified problem without providing information on what caused the miscommunication. Among open OIR are also the so-called meta-comments (Ekberg et al. 2020); a repair addressing the general acoustic signal with formulations like "I can't hear in this noise" or "I have a hearing problem you know." Restricted requests involve the interlocutor asking for clarification of a specific component of the trouble source, for example, by asking "who?," "where?," or "when?." Lastly, with restricted offers, the instigator provides a candidate interpretation of what was said, such as "did you say blue?" or "every what?."

To ensure the flow of a conversation and limit disruptions, restricted OIRs are preferred over open OIRs to help the sender resolve the OIR more easily (Schegloff et al. 1977; Clark & Wilkes-Gibbs 1986; Dingemanse et al. 2015). This is called the *principle of least collaborative effort*, which suggests that interlocutors will jointly minimize the overall effort associated with communicating with each other (Clark & Wilkes-Gibbs 1986; Rasenberg et al. 2022). Indeed, it has been found that the average length of repair solutions is shorter for more specific OIRs (Dingemanse et al. 2015), and the repair sequence is associated with lower joint effort (speech and gesture effort combined) relative to less specific OIRs (Rasenberg et al. 2022).

However, the principle of least collaborative effort can be challenged in difficult listening conditions, for example, when conversation partners experience HI and might not hear well enough to produce OIRs with high specificity. In free dyadic conversations, it has been observed that, relative to their NH conversation partner, HI interlocutors generally produce more OIRs, and a larger proportion of these are open OIRs (Lind et al. 2004, 2009; Pajo 2013; Laakso et al. 2019; Pajo & Laakso 2020, 2023). However, it should be noted that the relative distribution of open vs restricted OIRs differs significantly between studies, from ~90% (Ekberg et al. 2017) to just ~25% (Pajo & Laakso 2020) of OIRs being open. Within the open OIRs, it has also been reported that HI interlocutors, to a larger extent formulate them as meta-comments remarking on the unfavorable acoustic signal ("I'm not hearing you") (Ekberg et al. 2020), or even putting the burden of not hearing on themselves by using apologies ("Sorry, I cannot hear anything") (Ekberg et al. 2017).

It should be noted that not all studies of free conversations find differences in the number and type of OIRs between NH and HI interlocutors (Pajo & Laakso 2020; Ellis et al. 2024). In one study (Ellis et al. 2024), it was argued that this difference could be caused by the (unaided) HI interlocutor taking up a larger proportion of the speaking time, which is a strategy used by HI interlocutors to avoid having to listen and subsequently having to experience miscommunications. Another study found that relative to their NH conversation partner, aided HI interlocutors with mild-to-moderate hearing loss made the same number of OIRs, whereas HI interlocutors with severe to profound hearing loss initiated more OIRs (Pajo & Laakso 2020). Pajo and Laakso (2023) also looked at the timing of OIRs and found that interlocutors with severe HI uttered their OIRs in overlap with the trouble source to a larger extent than NH interlocutors and HI interlocutors with mild impairment. This was especially true for open OIRs, and a suggested cause was the HI interlocutor having/wanting to deal with the hearing problem as early as possible (Pajo & Laakso 2023).

It should be noticed that many of the studies mentioned above, although based on many hours of conversation, usually stem from a few participants and could thus be affected by individual differences in using OIRs (frequency, type, formulation, and/or timing of delivery). Furthermore, all previous studies focus on dyadic (two-talker) interactions. Although dyadic interactions are much more common than group conversation (>2 interlocutors) (Peperkoorn et al. 2020), dyads differ from larger group interaction by having simpler and more effortless turn-taking heuristics with a more well-distributed speaking time and requiring all (both) interlocutors to actively participate (Cooney et al. 2020). Hence, when experiencing a breakdown in mutual understanding between two interlocutors, this must be addressed, for example, through OIRs, to ensure that the dyadic conversation can continue. Indeed, it has been observed that in dyadic conversation, when an interlocutor has (unaided) HI, the NH interlocutor accommodates by speaking louder and slower (Petersen et al. 2022; Petersen & Parker 2024). However, in group conversations, it is possible for a subset of the interlocutors to continue a conversation even if one (or more) conversation partners cannot hear/understand what is being said.

The aim of the current paper is to explore the number and nature of miscommunication in a large dataset of conversations held between three interlocutors, of which one has HI. The analysis is based on an existing dataset (Petersen 2024) in which three interlocutors engage in free conversations in the presence of background noise presented at a low (50 dBC SPL) or high (75 dBC SPL) level and with the HI interlocutor experiencing different hearing aid (HA) signal processing schemes. At the low level of noise, the HI interlocutor is either unaided (condition denoted unaided) or wearing a HA with omnidirectional sound processing (aided). At the high level of noise, the HI interlocutor was always aided, but experienced omnidirectional sound processing (omni) or directional sound processing (dir) in which sounds originating from behind the HA wearer are suppressed. Quantifying and analyzing the miscommunications as OIR types (open and restricted), it is hypothesized that:

1. Increased communication difficulty caused by hearing impairment, less optimal HA processing, and increased noise leads to more miscommunications.
2. With increased communication difficulty, interlocutors will use more open OIRs when addressing these miscommunications.

Last, an exploratory analysis of the number of OIRs in relation to speech levels and degree of hearing impairment will be made. This analysis was included because previously published results of the same data showed interesting effects of listening conditions on the speech levels (Petersen 2024): When

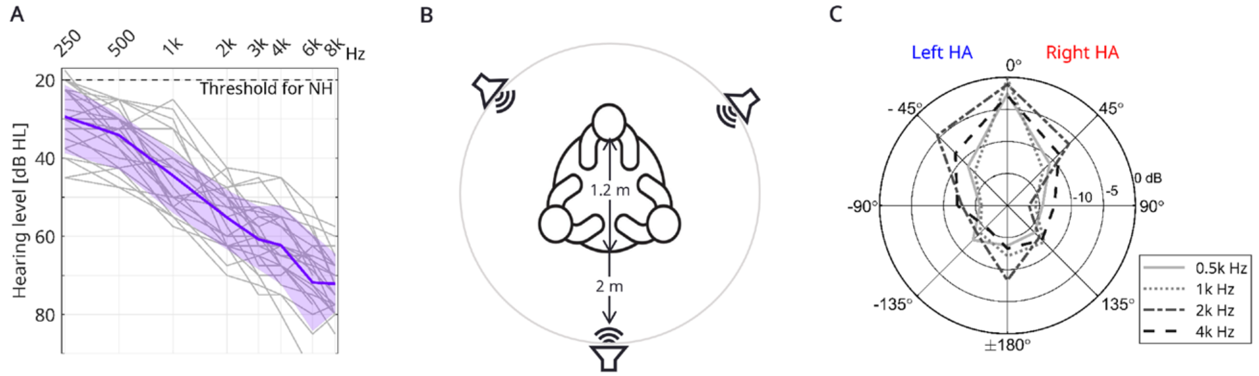

Fig. 1. Participants' audiogram and experimental setup. A, Individual pure-tone hearing thresholds for all HI participants averaged across ears (thin gray lines), participants (bold purple line), and the standard deviation (shaded purple area). B, Experimental setup with the three participants seated equally spaced around a table with a diameter of 1.2 m. A loudspeaker is placed 2.2 m directly in front of each participant. C, Attenuation of white noise when applying the directional sound processing experienced by the HI interlocutor at a high level of background noise (75 dBC, dir condition). The attenuation, in dB, indicated by concentric circles for different frequencies (line types and shading of gray), is shown for different azimuth angles. Note that the attenuations depicted for the negative azimuth angles stem from recordings from the left hearing aid (HA), while the attenuations at positive angles were recorded from the right HA. Figure adapted from Petersen 2024.

the HI interlocutor was unaided (low noise), all interlocutors spoke louder to make up for the reduced audibility compared to when the HI interlocutor wore HAs. When the noise level was increased, all interlocutors spoke louder, however the NH even more so because amplification alone (omni) does not improve speech intelligibility of the HI interlocutors in the presence of high background noise. Hence, as previously observed for dyadic conversation (Petersen et al. 2022; Petersen & Parker 2024), the two NH interlocutors in a triad regulate their speech levels to accommodate the hearing difficulties experienced by the HI interlocutor. In this relation, it was interesting to observe that when providing the HI interlocutor with noise-reducing directional sound processing (dir) in high noise, the HI interlocutor reduced their speech level, while this had no effect on the speech level of the two NH interlocutors.

MATERIALS AND METHODS

Data from the current study has previously been published by Petersen in 2024, which focused on the effects of noise, hearing loss, and hearing-aid processing on the features of the conversation dynamics, for example, the speech levels referred to in the introduction (Petersen 2024). For more details on the participants and experimental setup, please see (Petersen 2024).

Participants

A total of 25 groups of three previously unacquainted Danish-speaking interlocutors participated in the study. Each group was recruited to consist of one older HI interlocutor (>50 yo), one younger NH interlocutor (18 to 35 yo), and one older NH interlocutor (>50 yo). The HI interlocutors (mean age = 75.8, SD = 6.5, 9 females) were recruited from a database of volunteers who signed up for participation in audiological studies. The older NH (mean age = 54.8, SD = 3.7, 15 females) and younger NH (mean age = 27.2, SD = 5.2, 14 females) interlocutors were recruited internally among employees at WS Audiology, Lynge, Denmark. Of the NH employees at WS Audiology, three younger NH were studying audiology, while six of the older NH had an audiological background. The three interlocutor groups all differed significantly in age (all p's < 0.001). All NH interlocutors passed a hearing screening confirming hearing better than 20 dB HL (except for two older NH participants with 30 dB hearing levels in one ear at 4 kHz). In the current analysis, the younger and older NH participants will be treated as one combined group. The HI interlocutors had mild-to-moderate symmetrical hearing loss (mean pure-tone average across 0.5, 1, 2, and 4 kHz [PTA4] = 48.9 dB HL, SD = 6.1 dB HL, see Fig. 1A) and had used binaural hearing aids of various brands for >1 year and are thus considered experienced hearing-aid users. No cognitive screening tests were performed.

To test HA feature effects, the HI interlocutors were binaurally fitted with Signia Pure 312 7X receiver-in-the-canal hearing aids with M-receivers and closed-sleeve instant domes fitted with the NAL-NL2 prescription rule (Keidser et al. 2011). The hearing aids were fitted with two programs: One with omnidirectional processing in which all sounds from the surroundings were presented to the wearer, and one program with directional sound processing designed to suppress sounds originating from non-frontal positions. Using the Signia App, the pattern of attenuation in the second program was set to the narrowest possible width, providing around 10 to 15 dB attenuation of sounds beyond ±45° azimuth relative to the hearing-aid wearer (Fig. 1C).

All participants gave their written informed consent, and the study was conducted under an ethical waiver approved by the regional ethics committee (Board of Copenhagen, Denmark, reference H-20068621).

Experimental Setup

While sitting equally spaced (120° between interlocutors, see Fig. 1B) at a round table in an approximately 6 × 6 m meeting room (T60 reverberation time of 0.57 sec), the triads had a total of 12 conversations each lasting 5 min. Speech was recorded individually from each interlocutor using directional headset microphones (DPA 4088, Allerød, Denmark). Disturbing noise recorded from a canteen scene was presented from three loudspeakers positioned 2.2 m directly in front of each participant at 0 degrees azimuth. The noise was presented at 50 dBC SPL (low noise) during half of the conversations and 75 dBC SPL (high noise) for the other half. At each level of noise (low and high), the HI interlocutors experienced two different hearing-aid settings, while the NH interlocutors only experienced the two noise levels. At low noise level, the HI interlocutor was either not wearing hearing aids (condition denoted unaided) or was wearing hearing aids with omnidirectional sound processing (aided). In the high noise level, the HI interlocutor listened to omnidirectional sound processing (omni) or directional sound processing (dir) designed to suppress noise coming from the back and sides. Note that the hearing-aid settings were identical for the aided condition in low noise and the omni condition in high noise.

For each of the four conditions (unaided and aided in low noise, omni and dir in high noise), three 5-min conversations were recorded for each triad. The conversations were free, but initiated by providing either picture cards with potential discussion topics (e.g., concerts, sports, city life) or questions on which the group was to agree on an answer (e.g., 'If you had to agree to move to another country, which country would it be?").

The group was instructed to have a natural conversation, which could be based on the topic/question provided. No further instructions were given, and the participants were allowed to move freely (while staying seated in their chairs). Before the experiment, two 5-minute training conversations were held at a noise level of 60 dBC SPL to allow the interlocutors to get acquainted with each other, the experimental setup, and ways of initiating conversations (topics and questions).

Miscommunication Analysis

All conversations (25 Triads × 4 Conditions × 3 Repetitions = 300 conversations × 5 min = 25 hours of conversation) were listened to and the miscommunications transcribed by one of the authors. For the OIRs, the trouble source, OIR, repair solution, until the final repair confirmation was transcribed, see the example in Table 1. For non-OIRs, which do not follow the same pattern as OIRs, the parts that existed were transcribed, typically trouble source (accompanied by no response, see Table 1), or the sentence revealing the miscommunication (obvious wrong answers to a question).

After transcription, two authors of the paper categorized each instance of miscommunication as non-OIRs or OIRs, and the OIRs were further classified into the three types going from least specific "open requests," to "restricted requests," and most specific "restricted offers" (Dingemanse, Roberts et al. 2015). One of the two authors performed this categorization twice. Very few discrepancies between the three instances of categorization were found and resolved through mutual agreement between the authors. Last, the timing of the OIRs, sometimes denoted the Floor-Transfer Offset (FTO), was extracted as the gap (positive FTO) or overlap (negative FTO) in milliseconds between the trouble source turn and OIR.

The first part of the results presented in this paper focuses on all instances of miscommunications, while the second part focuses on the number and types of OIRs.

Statistical Analysis

For each individual interlocutor, the number of miscommunications was counted across the three 5-min conversations belonging to each condition (unaided, aided, omni, dir). A person was assigned a miscommunication if they uttered the OIR or if they were being addressed and did not respond/react as expected. In the examples provided in Table 1, both the OIR and non-OIR examples are assigned to the HI interlocutor. In one instance, a general question was asked with no response from any of the listeners. In this case, each non-responding interlocutor was assigned a miscommunication.

Using the lme4 package for R (Bates et al. 2015), a generalized linear-mixed effects model fit to a negative binomial distribution was used to investigate whether condition and hearing status (HI and NH) affected the number of miscommunications. All statistical models presented in the current study are based on the negative binomial distribution because the data exhibited overdispersion, i.e. the variance exceeds the mean. This happened because many participants did not have miscommunications, especially for conversations held in low noise, where only 6 of the 50 NH interlocutors had miscommunications. The negative binomial model was chosen because it had a significantly lower Akaike Information Criterion than a similar model based on a quasi-Poisson distribution and a negative binomial zero-inflated model. The final statistical model of the number of miscommunications included person as a random effect (miscommunications ~condition × hearing status + (1|person)). The post hoc differences of significant effects were tested using estimated marginal means implemented in the emmeans package in R (Lenth 2020) with FDR adjustments for multiple comparisons.

To investigate the relative distribution of open and restricted OIRs, the percentage of open OIRs of the total number of OIRs (open + restricted) was calculated. Interlocutors with no OIRs were omitted from this analysis. A negative binomial model was generated to investigate whether the ratio of open OIRs produced in the high noise condition was affected by condition and hearing status (proportion open OIRs ~condition × hearing status + (1|person)). In low noise, the NH produced very few OIRs, and the analysis was performed only on data from the HI interlocutors.

The effect of OIR type and hearing status on the timing of OIRs relative to the trouble source they addressed was tested using a linear mixed effects model including the timing of all

TABLE 1. Example transcriptions of OIR and non-OIR miscommunications. In the analysis of the data, for both examples, the miscommunication was assigned to the HI interlocutor

	OIR	Non-OIR
Trouble source	NH: Okay, how does that feel?	NH: How many kids do you have?
OIR	HI: What?	[no response]
Repair solution	NH: How does that feel?	NH: How many kids do you have?
Repair confirmation	HI: I feel that it overpowers everything else	HI: I have two kids

HI, hearing impaired; OIR, other-initiated repair.

individual OIRs (OIR FTOs ~condition x hearing status + (1|person)).

Last, an exploratory analysis was made to offer potential explanations for the number of OIRs produced by the NH and the HI interlocutors in conversations with a high level of background noise (omni and dir). For the HI interlocutors, the relationship between the number of OIRs (open and restricted) and their experienced degree of hearing impairment was investigated. The degree of hearing loss was quantified by PTA4, averaged across both ears. For the NH interlocutors, the relationship between the number of OIRs (open and restricted) and the speech level of their HI conversation partner was examined. The speech levels of the HI interlocutors were computed for the entire 5-min conversation, and the final HI speech level was calculated by averaging the levels of the conversations in which the NH uttered the OIRs. In this manner, a conversation with two OIRs was included twice in the calculation of the final average HI speech level, and speech levels from conversations without OIRs were not included. We focused on the HI speech levels as the results will show that the OIRs uttered by the NH interlocutors mainly addressed trouble sources made by the HI interlocutors. The OIRs in which NH interlocutors addressed trouble sources uttered by the other NH interlocutor were omitted from this analysis.

RESULTS

Miscommunications

Across 25 hr of conversations, the interlocutors had a total of 303 miscommunications, corresponding to one miscommunication being made every 4.9 min (by any speaker). However, as seen in Figure 2, both condition and hearing status affected the number of miscommunications. Although both hearing status [$X^2(1) = 44.9$, $p < 0.001$] and condition [$X^2(3) = 19.6$, $p < 0.001$] were significant main effects, the focus will be on the significant interaction between hearing status and condition on the number of miscommunications [$X^2(3) = 37.1$, $p < 0.001$]. The post hoc analysis of the interaction showed that the HI interlocutors had fewer miscommunications when they were aided relative to unaided ($z = 4.1$, $p < 0.01$), while the HI being aided did not affect the miscommunications made by the NH interlocutors ($z = 0.7$, $p = 0.48$). In both the aided ($z = 5.4$, $p < 0.001$) and the unaided ($z = 6.7$, $p < 0.001$) conditions, the HI interlocutor made more miscommunications than the NH interlocutors. When more background noise was present (aided vs omni), the number of miscommunications increased for all interlocutors (HI: $z = 2.4$, $p = 0.026$, NH: $z = 2.3$, $p = 0.025$). Although the number of miscommunications was reduced when providing directional sound processing to the HI interlocutor, there was no statistical difference between the two conditions ($z = 1.4$, $p = 0.19$). Noticeably, although there was no acoustic difference between omni and dir for the NH interlocutors, they had significantly more miscommunications in dir relative to omni ($z = 3.06$, $p < 0.01$). Although the HI interlocutors still produced more miscommunication in dir than the NH interlocutors ($z = 3.1$, $p < 0.01$), the difference between the two (HI versus NH) was significantly smaller in dir than in the omni condition ($z = 1.5$, $p < 0.001$).

Other-Initiated Repairs

Of the 303 miscommunications identified (Fig. 2), 255 of them were OIRs (Fig. 3). Of the 48 non-OIRs, 37 of them were made by HI in low noise. Examples of the most frequent non-OIR miscommunications are i) not responding to being addressed and ii) talking past each other without addressing it.

In conversations held in low noise, an OIR was instigated approximately every 7 min, while it was approximately every 5 min for conversations in high noise. Across conditions, open requests were by far the most prominent OIR [58.8%, $X^2(1) = 5.1$, $p = 0.02$], with restricted requests being by far the least used type of OIR (3.9%). Because of the limited number of restricted requests in general, the restricted requests and offers will be pooled and from here on denoted restricted OIRs.

At low noise levels, the proportion of open OIRs made by the HI interlocutors was significantly reduced by an estimated 56% when the HI interlocutor was aided relative to unaided [$X^2(1) = 5.1$, $p = 0.02$]. The distribution between open and restricted

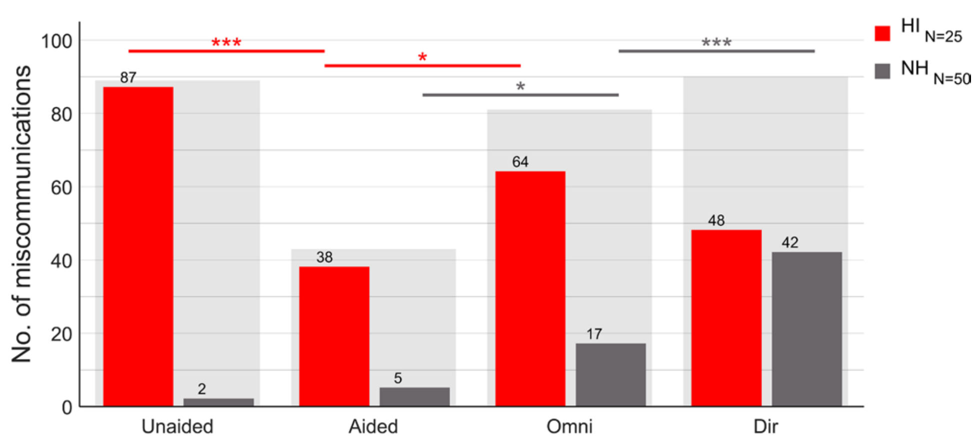

Fig. 2. Number of miscommunications across hearing status and miscommunications across hearing status and experimental conditions (noise level and HA processing). Numbers over the bars indicate the exact count. Light gray bars indicate the total number of miscommunications across hearing status. Horizontal lines indicate statistical significance between conditions for HI (red) and NH (dark gray). Note that in both graphs, the numbers are accumulated across 25 HI interlocutors, while the NH group includes 50 interlocutors. Asterisk indicating the significance level (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). HI indicates hearing impaired; NH, normal hearing.

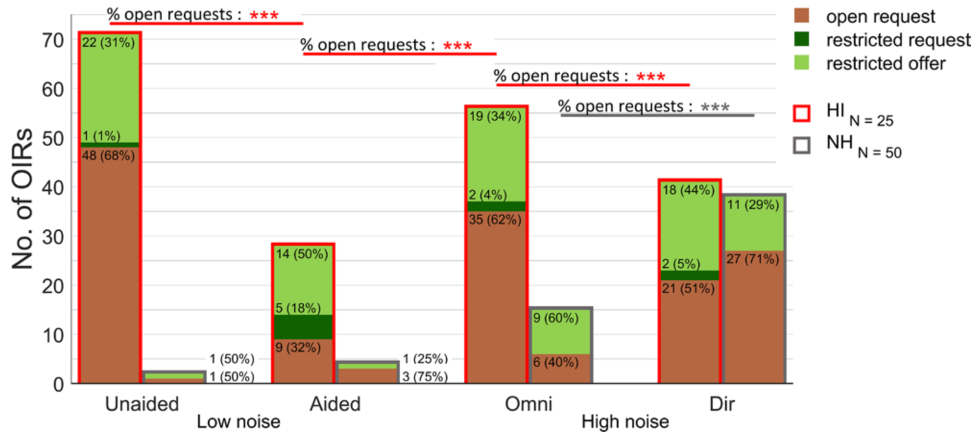

Fig. 3. Number and types of Other Initiated Repairs (OIRs). The number of the three different types of OIRs (open request, restricted request, restricted offer) across conditions and hearing status. Horizontal lines indicate statistically significant differences in the distribution of OIR types (percentage of OIRs being open requests) between conditions for hearing impaired (HI, red) and normal hearing (NH, dark gray) participants. Due to low numbers, no statistical analysis was performed for NH OIRs in the low-noise conditions. Note that the numbers displayed are accumulated across 25 HI interlocutors, while the NH group includes 50 interlocutors. Asterisk indicating the significance level (**p* < 0.05, ***p* < 0.01, ****p* < 0.001).

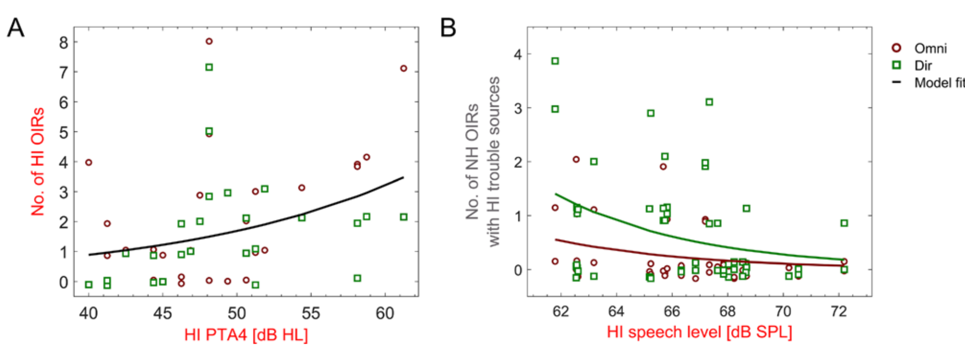

Fig. 4. Factors influencing the number of OIRs. A, The relationship between the degree of hearing loss, quantified by the PTA4, and the number of OIRs (open and restricted) made by the HI interlocutors. The black line indicates the negative binomial model fit (across omni and dir). B, The relationship between the HI speech level (across 5-min conversations) and the number of OIRs in which the NH interlocutor addresses a trouble source uttered by the HI interlocutor. As condition (omni and dir) significantly affects the HI speech level, model fits from both conditions are included in the graph. HI indicates hearing impaired; NH, normal hearing; OIR, other-initiated repair.

OIRs was not analyzed for the NH interlocutors in conversations held at low noise because of their scarcity.

At high noise levels, the proportion of open OIRs was affected by condition [$X^2(1) = 40$, $p < 0.001$], as well as an interaction between hearing status and condition [$X^2(1) = 70.5$, $p < 0.001$]. The post hoc analysis of the significant interaction revealed that while the ratio of open OIRs decreased for the HI between omni and dir ($z = -6.3$, $p < 0.001$), the opposite was true for the NH interlocutors, where the ratio of open OIRs increased when the HI received directional sound processing ($z = 5.6$, $p < 0.001$). When inspecting the number of open and restricted OIRs in Figure 3, it is evident that these changes in the proportion of open OIRs between omni and dir are driven by changes in the number of open OIRs, as the number of restricted OIRs changes very little from omni to dir. For the HI interlocutors, the number of open OIRs decreased from 35 to 21 between omni and dir, whereas the number increased from 6 to 27 for the NH interlocutors.

The OIRs were generally timed with a gap of 460.5 msec (median FTO) after the trouble source, with a variability of 877.75 msec (interquartile range of all FTOs). However, the analysis of these FTO values showed that neither hearing status ($p = 0.98$), type of OIR ($p = 0.27$), nor their interaction ($p = 0.37$) significantly affected the timing with which the OIRs were uttered.

A more detailed look into who uttered the trouble source causing the NH interlocutors to make OIRs showed that in the omni condition, the HI interlocutor uttered the trouble source for 13 of the 15 OIRs (86.7%, 6 of the open and 7 of the restricted OIRs). For the dir condition, the OIRs were directed at trouble sources uttered by the HI for 34 of the 38 OIRs (89.5%, 24 of the open and 10 of the restricted OIRs). Hence, the OIRs uttered by the NH interlocutors were mainly directed at trouble sources uttered by the HI conversation partners.

Factors Affecting the Number of OIRs

An exploratory analysis was done to investigate potential explanations for the number of OIRs observed for the HI and NH interlocutors in the conversations held in noise. For the HI interlocutors, an increase in the number of OIRs (open and restricted) across the conditions (omni and dir) was seen for HI interlocutors with poorer hearing [higher PTA4, $X^2(1) = 5.9$, $p = 0.015$, see Fig. 4A].

Inspired by the previous observation that HI interlocutors significantly reduced their speech levels in the dir condition (Petersen 2024), in combination with the present result that the NH interlocutors had more and a larger proportion of open OIRs in dir than in omni, we next explored the relationship between HI speech levels and the number of OIRs (open and restricted) made by the NH interlocutors because of a trouble source uttered by the HI interlocutor. Figure 4B shows the number of OIRs made by the NH interlocutors and the speech level of the HI interlocutor. To account for the significant effect of condition on the HI speech level found in (Petersen 2024), the negative binomial model included both person and condition (omni and dir) as random effects. The results showed that the total number of OIRs in which the NH interlocutor addresses trouble sources uttered by the HI conversation partner is significantly reduced when the HI speaks louder [$X^2(1) = 37.2$, $p < 0.001$].

DISCUSSION

In free triadic conversations, it was observed that the HI interlocutors have more miscommunications than their NH conversation partners and that noise level causes an increase in miscommunications for all interlocutors (Fig. 2). In low noise levels, the number of miscommunications is reduced when the HI interlocutor wears a hearing aid (aided). While not affecting the miscommunications of the HI interlocutors listening to directional sound processing compared with omni, their NH conversation partners made more miscommunications when the acoustic experience of the HI talkers was improved by dir (Fig. 2).

In the subset of miscommunications that were formulated as OIRs, the less specific open OIRs were used significantly more than the more specific restricted OIRs (Fig. 3). While more noise increased the proportion of open OIRs used by the HI interlocutors, both hearing-aid amplification and directional sound processing caused a decrease in the proportion of open OIRs used. Again, the directional sound processing experienced by the HI interlocutor also affected the NH conversation partners who used open OIRs to a larger extent.

Last, more OIRs (open and restricted) were produced in high noise levels by the HI interlocutors suffering from worse hearing (Fig. 4A). For the NH interlocutors, who mainly produce OIRs in response to trouble sources uttered by the HI interlocutors, the number of OIRs significantly reduced when the HI conversation partner spoke louder (Fig. 4B).

In the remainder of the discussion, the current observations will be compared with previous findings, however it should be noted that comparing conversations between groups of different sizes, involving interlocutors with different interpersonal relationships and different degrees of conversational freedom, should be done with care. The results of the current study are based on data from a controlled experimental procedure, which might limit how well the results generalize to spontaneous conversations observed in everyday life. However, because the underlying structure of any conversation follows the same rules for turn-taking, informational exchange, as well as OIR formulations and repair mechanisms, we would argue that conversations overall have a relatively large degree of generalizability. In the current study design, we controlled the external environment and group constellation, however the primary stimuli, that is, the conversations, were not controlled. We will therefore argue that the experiment does exhibit some degree of ecological validity according to the definition put forth by Keidser et al. (2020), as the conversations "reflect real-life hearing-related function, activity, or participation".

Miscommunication and OIRs in Triadic Conversations

In the triadic interactions presented in the current study, a conversation can persist as long as two of the three interlocutors have mutual understanding, however the number of miscommunications observed in the current study suggests that interlocutors generally initiate a repair if they experience a breakdown in the shared mutual understanding. Although it has been noted that HI interlocutors might use strategies such as pretending to hear or not participate actively in the conversation (Pajo & Laakso 2020), the number of miscommunications in the current study suggests that the HI interlocutors did not adopt these disengaging strategies. On the contrary, the alternative strategy was observed for the current dataset, namely that the HI interlocutors speak more, around 7% more than the NH individuals (Petersen 2024). Hence, the high number of miscommunications is observed even though the HI interlocutors listen less during the conversations than their NH conversation partners. Indeed, it might be speculated that the HI interlocutors, consciously or unconsciously, adopt the strategy of monologuing to avoid having to listen (Stephens & Zhao 1996).

A total of 84% of the miscommunications were formulated as OIRs, with OIRs occurring every ~7 min in low background noise and every ~5 min in high. These rates of OIRs are comparable to the 5-min interval observed between OIRs initiated in two-person conversations across different cultures (Dingemanse et al. 2015). Of all the OIRs observed, the least specific open OIRs were by far the most frequently used (58.8%), while the restricted requests were the least used (3.9%). It is interesting that open OIRs are generally found to be much less frequent in dyadic conversations, with rates between 6 and 31% for NH interlocutors (Pajo 2013; Kendrick 2015; Rasenberg et al. 2022; Pajo & Laakso 2023) and between 41 and 44% for HI interlocutors (Pajo 2013; Pajo & Laakso 2023). Specifically for the HI interlocutors conversing aided in quiet, we observed that 32% of the OIRs were open, which is comparable to the ~25% open OIRs previously identified for aided HI interlocutors in dyadic conversation (Pajo & Laakso 2023). Although the number of OIRs can be difficult to compare between dyadic and triadic conversations, it is interesting to note that the proportion of open OIRs seems unaffected by group size when HI interlocutors communicate in quiet.

The relatively large proportion of open OIRs observed in the current study seems to oppose the "principle of least collaborative effort" (Clark & Wilkes-Gibbs, 1986; Rasenberg et al., 2022). One possible explanation for the large proportion of open OIRs in the current data could be that the triadic conversation held in noise has more trouble-prone speech, that is, more speech overlaps than dyads and more speech masked by the background noise and hearing loss, factors that have previously been described as causing OIRs (Drew 1997; Laakso et al. 2019). Indeed, previous analysis of the triadic conversations showed that the median turn-taking times (floor-transfer offsets) were negative, hence talkers were speaking in overlap (Petersen 2024), and talkers produced around 3.6 verbal backchannels per minute in overlap with the main talkers' speech (Petersen et al. 2023). When noise and speech-overlap affect intelligibility, it is no longer possible for interlocutors to formulate more restricted OIRs, which causes the "principle of least collaborative effort" to break down as interlocutors are only able to hear enough to formulate open OIRs.

In the current data, no effect of hearing or OIR type was found on the timing of the OIRs relative to the trouble source. Hence, our results do not concur with previous observations that HI interlocutors deliver their OIRs, especially the open OIRs, faster than the NH interlocutors (Pajo & Laakso 2023). It should be noted however, that the values reported by Pajo and Laakso (2023) stem from a total of just 18 OIRs (8 open and 10 restricted OIRs) for mild-to-moderate HI interlocutors, which can affect the reliability of the results. However, although the response times for open OIRs uttered by NH interlocutors were somewhat similar in the study by Pajo and Laakso and in an earlier study by Kendrick (2015), Kendrick observed that restricted OIRs were uttered with a shorter delay than the open OIRs. In both studies, conversations were dyadic interactions between friends and family members, which might have a significance on how OIRs are formulated and timed, as interruptions are more socially acceptable between acquainted interlocutors, however at the same time, triadic conversations also limit how long you can delay your OIR, as the conversation might move on between the remaining two interlocutors.

Amplification Improves, but Does Not Remove, Miscommunications

In low noise, a total of 7 miscommunications were found for the NH interlocutors (Fig. 2), corresponding to 1 per 3.5 hr of conversation. This very low number could be caused by the elevated speech levels produced by all interlocutors, especially when the HI interlocutor is unaided (Petersen 2024). For the HI interlocutors, providing hearing aids significantly reduced the number of miscommunications, but even in the aided condition, HI interlocutors still have more miscommunication than their NH conversation partners. The reduced audibility experienced by the HI interlocutors can be compensated for by HA amplification, however, HAs cannot compensate for the reduced frequency selectivity of the HI interlocutors, which makes it difficult to distinguish speech and noise signals (Moore 2003). Despite not eliminating miscommunications, HA amplification does cause the HI interlocutors to make more specific restricted OIRs, which require lower joint effort to solve than open OIRs (Rasenberg et al. 2022).

Directional Sound Processing Affects All Interlocutors

When the noise level increases, the number of miscommunications increases for all interlocutors, and the proportion of open OIRs increases for the HI interlocutor. In high noise, providing directional sound processing to the HI interlocutor resulted in numerically fewer miscommunications, but the change from omnidirectional was not statistically significant. However, the proportion of open OIRs significantly decreased. As directional sound processing causes an improved SNR by attenuating noise originating from behind the HI interlocutor, it is not surprising that this improved SNR causes a change in the type of the OIR used: If an utterance is completely unintelligible, the corresponding OIR is bound to be open, whereas restricted OIRs can only be formulated for partly intelligible trouble sources. However, NH interlocutors were observed to have more miscommunication and use open OIRs to a larger extent when the HI interlocutors experienced directional processing, which was an unexpected observation.

From previous analysis of the conversations, it was found that the HI interlocutors spoke at –7 dB SNR in omni, which reduced to –8.5 dB SNR in dir (Petersen 2024). It has previously been argued that speech levels are increased when conversation partners exhibit behavior which indicates that they cannot hear (Beechey et al. 2020), and indeed it has been found in dyadic conversations that the NH interlocutor regulate their speech levels to match that of their unaided HI conversation partner (Petersen & Parker 2024). Hence, speakers will signal difficulty through their speech levels, and conversation partners will adapt their own levels to match what they hear. In the context of the current study, HI interlocutors in dir decreased their speech levels as their auditory experience improved, however this decrease in speech level was not matched by their NH conversation partners, most likely because the NH interlocutors were now struggling to hear. This inability to hear the HI conversation partner is evident from the increase in the number of miscommunications made by the NH interlocutors and a larger proportion of open OIRs. Why the HI interlocutor in dir does not adapt their speech levels to those of the NH interlocutors is unknown, but it might be speculated that the directional sound processing influences the subjective feeling and perception of the HI interlocutors' own voice levels, making it difficult, or socially inappropriate, for them to increase their speech levels.

Included in the previous publication of the current dataset (Petersen 2024) was the analysis of the ratings, provided after each conversation, of the interlocutors' perceived participation and use of communication strategies. It is interesting that although both ratings were sensitive to changes in noise level and the HI rated using more listening strategies when unaided, no difference in any of the measures was found between omni and dir (Petersen 2024). This suggests that the NH interlocutors did not notice their increased usage of OIRs in the dir conditions or did not think to include it when evaluating their rating using communication strategies, with the instruction text including "by changing the way you express yourself, use your voice or body language" (Petersen 2024).

When evaluating the influence of speech levels on the OIRs, NH interlocutors had fewer OIRs (open and restricted) in conversations where the HI interlocutor spoke louder in high noise (omni and dir, Fig. 4B). Although the speech levels in this analysis were aggregated across the entire conversations, and not relating to specific trouble sources or intervals around, the relation between speech levels and number of OIRs by the NH interlocutors was strong ($p < 0.001$). This highlights the complexity of conversations: A single (HI) interlocutors' acoustic experience can alter the behavior of the entire group conversation.

No relationship existed between HI interlocutors' number of OIRs and the speech levels of the NH interlocutors, however significantly more OIRs were observed in high noise for HI interlocutors experiencing worse hearing loss (Fig. 4A). This relationship highlights how even a group of HI individuals may differ and that the degree of hearing loss is an important factor when investigating how they affect communication. Indeed, it has been previously reported that HI interlocutors with mild hearing loss did not make as many OIRs as their NH conversation partner, whereas differences were observed for HI interlocutors with severe to profound hearing loss (Pajo & Laakso 2020).

Before summarizing our observations, it is important to acknowledge that the "cost" of uttering an OIR can be very different for a HI interlocutor: HI interlocutors might feel that asking for clarifications causes irritation with their conversation partner (Laakso et al. 2019) or, in other ways, be stigmatizing (Southall et al. 2010). Indeed, it has described how HI interlocutors use apologetic OIRs, for example, "Sorry?" or "Beg your pardon?," to put the burden of the communication breakdown on themselves (Ekberg et al. 2017). It might be reasonably assumed that NH interlocutors do not have the same feelings associated with asking for clarifications.

CONCLUSION

In summary, this study is the first of its kind, showing that in a large dataset of triadic conversations held in controlled settings, more miscommunications occurred with a larger proportion of open OIRs as the noise level was increased. Hearing-aid amplification reduced the number of miscommunications and the proportion of open OIRs for the hearing-impaired interlocutor in low noise. In high noise, directional sound processing reduced the proportion of open OIRs for the HI interlocutor, but also caused the NH interlocutors to have more miscommunications with a larger proportion of open OIRs. Further analysis revealed that the directional processing caused HI interlocutors to reduce their speech levels, thereby resulting in the NH interlocutors having more OIRs. In conclusion, our results show how miscommunications and OIRs are affected by the shared acoustic experience (noise level), but also by triadic conversations, the auditory experience of a single interlocutor (the HA processing of HI interlocutors). However, it is important to note that the subjective experience of uttering an OIR can be very different for people suffering from HI: Normal-hearing interlocutors will probably assume that not hearing something is caused by the speech produced by their conversation partner, hence, they are not directly the cause of the disruption of the conversational flow. People with HI, on the other hand, will most likely blame their own hearing loss and feel that uttering an OIR will draw attention to their impairment.

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