Auditory Environments and Hearing Aid Feature Activation Among Younger and Older Listeners in an Urban and Rural Area

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Objectives: The purpose of this study was to investigate differences in auditory environments and hearing aid feature activation between younger listeners with normal hearing and older listeners with hearing loss in an urban and rural location. We hypothesized that (1) urban dwellers and younger listeners would encounter more diverse and demanding auditory environments than rural dwellers and older listeners, respectively; (2) the advanced hearing aid features (noise reduction and directional microphone) of urban dwellers and younger listeners would be activated more frequently than rural dwellers and older listeners, respectively.

Design: The design of this study was cross-sectional with repeated measures. A total of 12 older adults with hearing loss (OHL-U) and 11 younger adults with normal hearing (YNH-U) were recruited from an urban area (Berkeley, California) and 13 older adults with hearing loss (OHL-R) and 10 YNH-U were recruited from a rural area (Iowa City, Iowa). Participants wore hearing aids that recorded data about their listening environments and completed ecological momentary assessments for 1 week.

Results: The YNH-U group experienced higher sound pressure levels and hearing aid features were activated more frequently than in the OHL groups. The OHL-R group experienced significantly less diverse sound pressure levels than the YNH-U group. The YNH-R group had sound levels between the YNH-U group and the OHL groups but without significant differences from any other group. The YNH groups showed a greater likelihood of hearing aid feature activation than the OHL-R group.

Conclusions: Demographics affect auditory environments and the activation of hearing aid features. Younger urban dwellers have the most diverse or demanding auditory environments and hearing aid feature activation, and older, rural dwellers with hearing loss have the least diverse or demanding auditory environments and hearing aid feature activation. Future studies of real-world auditory environments and audiology intervention effectiveness should consider location in recruitment and interpretation of results.

Key words: Auditory environment, Auditory ecology, Hearing aids.

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INTRODUCTION

The United States is an increasingly urban nation. In 1910, 54.4% of the US population lived in rural areas; in 2010, just 19.3% of the population lived in rural areas (U.S. Census Bureau 2016). It is not just young people driving the urban boom. Although the median age of the rural dweller is indeed older, at 51 years, the median age of the urban dweller is not substantially younger, at 45 years (U.S. Census Bureau 2016). Urban life in the United States is notably different from rural life in many ways (e.g., Parker et al. 2018). These differences in lifestyle can contribute to differences in health outcomes between these populations, with typically poorer outcomes for rural populations (e.g., Eberhardt & Pamuk 2004; Haggerty et al. 2014). It may be of interest for audiologists, then, to understand if there are differences in auditory environments between rural and urban populations that might inform treatment recommendations and intervention outcomes. The purpose of this study was to investigate potential differences in auditory environments and hearing aid feature activation between urban and rural locations as well as the role of age and hearing loss in these differences.

Recent years have seen an increase in research on the real-world auditory environments of hearing aid users and their impact on hearing aid preferences and effectiveness (e.g., Gatehouse et al. 1999; Gatehouse et al. 2003; Noble 2008; Wu et al. 2018; von Gablenz et al. 2021; for a review, see Keidser & Naylor 2020). Auditory environments have been characterized and quantified using a variety of methods and metrics. Environments are typically measured using subjective measures, particularly retrospective questionnaires such as the Auditory Lifestyle and Demand Questionnaire (ALDQ; Gatehouse et al. 1999; Cox et al. 2011; Wu & Bentler 2012), or surveys completed in situ, ecological momentary assessment (EMA; Wu et al. 2018; Holube et al. 2020; von Gablenz et al. 2021; Wu et al. 2021), or objectively using sound pressure levels, signal to noise ratios, and sound classification (e.g., Walden et al. 2004; Gatehouse et al. 2006b; Wu & Bentler 2012; Smeds et al. 2015; Humes et al. 2018; Klein et al. 2018; Wu et al. 2018).

The overall finding of studies investigating the auditory environments of adult hearing aid users is that adult hearing aid users may not generally encounter very diverse or demanding auditory environments. For example, Smeds et al. (2015) found that hearing aid users rarely encountered environments with negative signal to noise ratios, and that even when background noise was present, the signal to noise ratio was favorable—on average 5 dB. Wu et al. (2018) further found that older adult hearing aid users most commonly encountered quiet environments where the signal of interest was in front of them. Klein et al. (2018) found that older adults spent the most time in quiet (40%), followed by television watching (26%), and then meaningful speech (12%). Very little time was spent in noisy environments (less than 6% of the time). Several other studies

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using a variety of methods including paper and pencil journals and hearing aid data-logging have found similar results, with adult hearing aid users spending up to 75% of the time in environments with favorable acoustic conditions, either quiet or at least relatively high signal to noise ratios (Walden et al. 2004; Keidser 2009; Banerjee 2011; Humes et al. 2018; Wu et al. 2018; Andersson et al. 2021). Of note is that the studies about auditory environments do not always show consistent results. For example, the hearing aid users in von Gablenz et al. (2021) spent approximately 30% of their time in quiet and more time in conversation (28%), whereas hearing aid users in Klein et al. (2018) spent more time in quiet (40%) and less time in conversation (12%). Although this difference could be due to several considerations, demographic differences could be a contributing factor. For example, data logging from cochlear implant users suggests that the types of auditory environments cochlear implant users encounter may depend on what country they live in (Busch et al. 2017).

Although detailed location information for participants in the aforementioned studies has not been reported, it seems likely that these studies primarily included participants from rural or less densely populated areas—Iowa City, Iowa, Bloomington, Indiana, Odense, Denmark, and Oldenburg, Germany, although at least one study likely had participants from the more urban Minneapolis, Minnesota. Urban dwellers and rural dwellers might not experience similar auditory environments. Urban dwellers may encounter more demanding and diverse auditory environments with greater listening demands since urban soundscapes are generally louder than rural soundscapes (e.g., CalTrans 1998; Albert & Decato 2017). The types of noises in urban soundscapes differ from those commonly encountered in rural soundscapes. Urban soundscapes consist of a large variety of man-made noises, whereas rural soundscapes largely include the sounds of nature (e.g., Southworth 1969; Joo et al. 2011; King et al. 2012). Further, rural dwellers may have smaller social networks than urban dwellers and rural dwellers' social networks may contain more family members and fewer friends relative to urban dwellers' networks (Fischer 1982; Gilbert et al. 2010), although this may not be true for all cultures, places, or times. If true; however, the larger and more diverse social networks of urban dwellers might be expected to lead to more diverse and demanding auditory environments (Wu & Bentler 2012).

In addition to dwelling location, age is another factor that could affect auditory environments. For example, older adults may be expected to encounter fewer noisy environments than younger people. Older adults have generally been found to be less socially active than younger adults, and this may extend to differences in auditory environments (for a review, see Marcum 2013). Wu and Bentler (2012) investigated whether younger adults encountered more demanding auditory environments than older adults by characterizing the associations among age, sound pressure levels encountered in the real world, social network size, and auditory lifestyle as measured by the ALDQ for both age groups. They found that older age was associated with lower overall sound pressure levels and smaller social networks, but ALDQ scores were not associated with age, social network size, or sound pressure levels.

Understanding whether demographic factors like age and location affect auditory environments could inform audiologic intervention and shed light on outcome variability. For example, if younger, urban-dwelling hearing aid users are found to have more diverse auditory environments than older, rural-dwelling hearing aid users, it might be expected that the younger, urban-dwelling users experience greater benefit from more intensive interventions or advanced hearing aid technologies. Supporting this scenario, Gatehouse et al. (2006b) found that auditory environment diversity and demand, as quantified by the ALDQ and sound-level variance in the daily lives of participants, were associated with greater benefits from fast-acting compression than linear amplification. In Wu et al. (2019), premium-level hearing aids did not outperform basic-level hearing aids in the real world. They posited that one reason for this difference might have been that participants were older, rural-dwelling adults; thus, their auditory environments might have been too limited to show benefits from premium-level hearing aids and hearing aid features. Finally, Christensen et al. (2021a,b), using a real-time hearing aid data tracking paradigm, found that hearing aid use increased on days when users encountered higher sound pressure levels, lower signal to noise ratios, and more diverse auditory environments.

Taken together, there is a multidisciplinary body of work that suggests that auditory environments and hearing aid feature activation may differ between urban and rural dwellers and between younger and older adults. Whether this is the case is unknown. This study aimed to address this gap by answering the following specific research questions:

1. What is the effect of demographics (urban versus rural location and younger listeners with normal hearing versus older listeners with hearing loss) on auditory environments?
2. What is the effect of demographics (urban versus rural location and younger listeners with normal hearing versus older listeners with hearing loss) on hearing aid feature activation (directional microphones and gain reduction)?

To answer these questions, we collected data from the daily lives of participants. Data included hearing aid measurements (input sound pressure level, directional microphone activation, gain reduction, and sound classification), as well as EMA (self-reported listening activity and noise level). Participants also completed the ALDQ. We hypothesized that (1) urban dwellers and younger listeners would have more diverse (i.e., a larger variance of sound pressure levels within and between listening environments, higher ALDQ scores) and demanding (i.e., higher sound pressure levels, higher background noise levels, more conversation, and less passive listening) auditory environments than rural dwellers and older listeners, respectively and (2) urban dwellers and younger listeners would have greater hearing aid feature activation than rural dwellers and older listeners, respectively.

MATERIALS AND METHODS

Participants

A total of 46 participants were recruited for this study. Participants were in one of four groups: younger participants with normal hearing in a rural area (YNH-R), younger participants with normal hearing in an urban area (YNH-U), older participants with hearing loss in a rural area (OHL-R), and older participants with hearing loss in an urban area (OHL-U). Rural participants were recruited at the University of Iowa in Iowa

City, Iowa, and urban participants were recruited at the Starkey Hearing Research Center in Berkeley, California. Participants were recruited through mass email, advertisements, existing databases of past participants, clinical referrals, and word of mouth. Defining rural and urban areas is complex, and there are no simple delineations for characterizing an urban or rural location. Iowa City, Iowa and Berkeley, California were deemed reasonable representations of rural and urban environments. The population density of Iowa City is 2713 inhabitants per square mile, while the population density of Berkeley is 11,474 inhabitants per square mile (U.S. Census Bureau. 2019). The population density of Johnson County, Iowa, which contains Iowa City, is just 212.9 inhabitants per square mile, while the population density of Alameda County, California, which contains Berkeley, is 2047.6 inhabitants per square mile (U.S. Census Bureau. 2019). Berkeley, California is part of one of the largest metro areas in the United States, whereas Iowa City is surrounded by farmland.

Groups were matched for age and hearing loss (YNH-U: n = 11, female = 5, mean age = 26.5 years, SD = 4.6; OHL-U: n = 12, female = 6, mean age = 65.5 years, SD = 4.12; YNH-R: n = 10, female = 6, mean age = 25.6 years, SD = 6.5; OHL-R: n = 13, female = 5, mean age = 66.2 years, SD = 4.13). Audiograms for all groups are shown in Figure 1. All participants with hearing loss were experienced hearing aid users (at least 6 months of hearing aid use). Participants in the OHL groups were generally retired, although most were active in volunteer, religious, and other social communities. Participants in the YNH groups were working professionals, students, or a combination of both, and most also indicated that they were active in a variety of volunteer, religious, and other social groups. All participants consented to the study before commencing participation. The Institutional Review Board at the University of Iowa approved this study. Participants were compensated $15/hour for visits to the laboratory and $1 per survey completed during the week. Data were collected continuously from mid-2017 to early 2019.

Procedures

Participation included two visits to the laboratory with a 1-week field study in between. On Visit 1, participants completed audiometry, were fit with research hearing aids, and were trained on hearing aid use and EMA. During the field study, participants wore the research hearing aids and carried a smartphone connected to the hearing aids via Bluetooth. Two types of data were collected: hearing aid processing data and EMAs completed via the smartphone via the smartphone. All data were stored on the smartphone. Participants were asked to collect data for 12 to 16 hours per day, in a window chosen by the participant to fit their lifestyle (i.e., waking and sleeping hours). The EMA app (AudioSense+: Hasan et al. 2013; Wu et al. 2015) was programmed accordingly. After 1-week, participants returned to the laboratory to complete questionnaires.

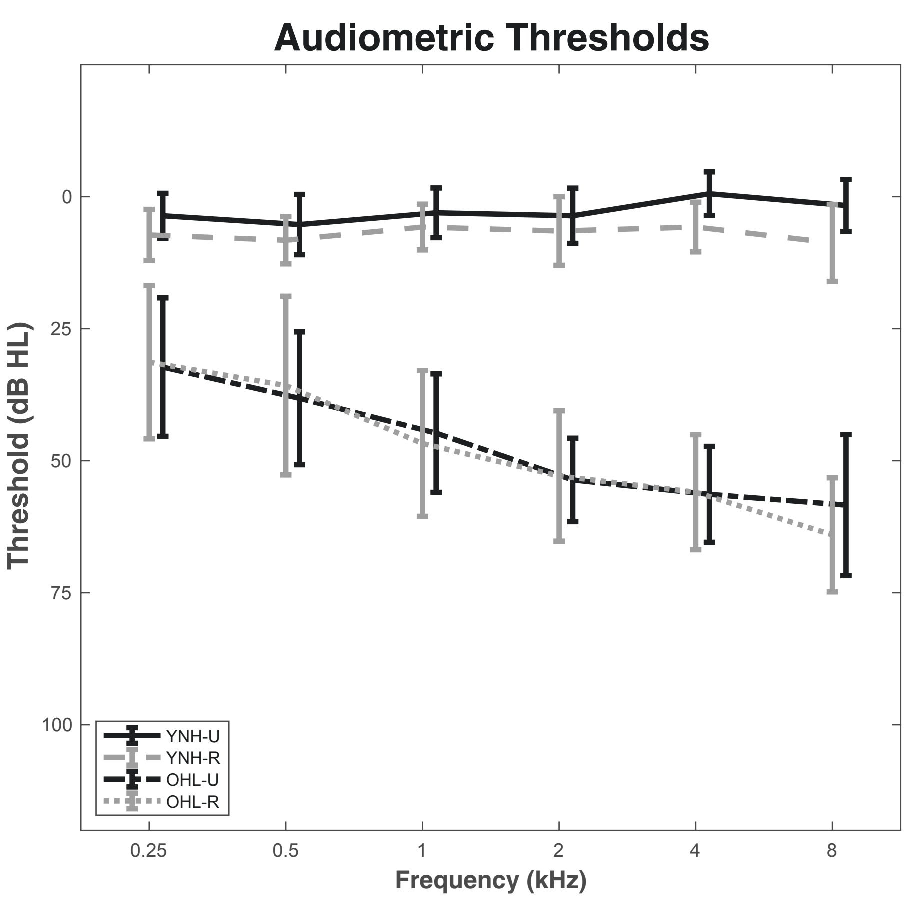

Fig. 1. Mean and SDs (averaged across ears) of audiometric thresholds for YNH groups (top) and OHL groups (bottom). OHL, older participants with hearing loss; YNH, younger participants with normal hearing. OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

Hearing Aid Fitting

Participants were fit bilaterally with Starkey Halo 2 i2400 receiver-in-the-canal hearing aids. The hearing aids used research firmware to record the hearing aid processing state on a smartphone. Hearing aids were fit using the method described in a study by Xu et al. (2020). For participants with normal hearing, the hearing aids acted as sensors. They were programed to have zero gain in all channels and participants wore them with open domes. No real-ear measurements were performed for participants with normal hearing. For participants with hearing loss, the research hearing aids were fit to match the gain settings of their personal hearing aids to the degree possible. To do this, real-ear measurements were made of the participant's personal hearing aids at 55, 65, and 75 dB SPL using the "carrot passage" on an Audioscan Verifit 2 (Audioscan, Dorchester, ON). Maximum power output was measured using an 85-dB SPL pure-tone sweep. Then, the research hearing aids were programed so that the real-ear response of the research hearing aids matched the response of the participant's personal hearing aids within 5 dB from 0.5 to 4 kHz. Maximum power output was also matched to the degree possible. Priority was given to matching output for the 65 dB SPL input when compression ratios could not be made adequately similar between the personal and research hearing aids to match gain within 5 dB for all input levels. For participants with hearing loss, volume control was enabled. All participants were trained on the use and care of the hearing aids, including a demonstration and practice of putting the hearing aids on and changing the hearing aid batteries.

Hearing Aid Data

Because of power constraints on both hearing aids and smartphones, data were collected periodically rather than continuously. The mobile application attempts to collect a data snapshot at a preconfigured fixed time interval. These attempts can either succeed or fail, depending on whether a reliable Bluetooth connection between the phone and the hearing aid can be established. Connection failures typically occur when the phone and the hearing aid are not collocated although other technical issues cannot be excluded. When a connection is established successfully, the snapshot includes the processing state of the hearing aid at a sampled rate of 2 Hz during each snapshot. If no connection can be established, no snapshot is recorded. The application did not record the outcome of each connection attempt, and thus, it is not possible to discern how often the connection was unstable.

A subset of the snapshots—which we will refer to as EMA-associated snapshots—also included responses to EMA surveys. Snapshots without EMA responses are referred to as non-EMA snapshots. The mobile application attempted to collect a non-EMA snapshot every 10 minutes. Each non-EMA snapshot includes hearing aid processing data collected for one minute and did not require any action by the participants. The mobile application attempted to collect EMA-associated snapshots approximately every 40 minutes. An EMA-associate snapshot includes the hearing aid processing data collected for 5 minutes before and after the completion of an EMA. For EMA-associated snapshots, only the first five minutes of hearing aid data (recorded before the EMA delivery) were used in the analysis. For non-EMA associated snapshots, data from the entire 1-minute collection period were used.

Measurements of the auditory environment and measurements of hearing aid feature activations were recorded. To characterize the effect of dwelling location and subject group on auditory environments, the primary objective measure used was SPL estimates from the environment using the hearing aid broadband input level. SPL estimates from the hearing aid were achieved using a similar procedure as in Banerjee (2011), with updated procedures for the Halo 2 provided by Starkey. Level estimates were made for each of the 24 channels every 10 ms. Then, static, frequency-specific transforms were used to estimate the free-field level at each ear, removing microphone location effects. Microphone and pre-amp gain corrections were applied. These values were converted to dB full scale and summed. Then, an estimation of the SPL was made by applying a correction factor. The SPL estimation comprised any sound being received by the hearing aid. SPL at the input of the hearing aids has been used to characterize differences in auditory environments as a function of median level, within-snapshot level variance, and between-snapshot level variance (Gatehouse et al. 2006a; Wu & Bentler 2012). In the present study, within-snapshot variance was calculated by finding the SD of the broadband input levels of all samples within each snapshot. Between-snapshot variance was calculated by first finding the median input level of samples within each snapshot and then calculating the SD of the median input levels across snapshots. Within-snapshot variance then indicates how much sound levels were fluctuating within a single environment, whereas across-snapshot variance indicates how much sound levels fluctuated in a participants' life more generally. Differences in median level and level variance between left and right hearing aids were calculated, but differences between hearing aids were small and thus all level analyses used values averaged between both hearing aids.

The sound classifications made by the hearing aids for each snapshot were also analyzed. The exact heuristics the hearing aids used to classify sounds are proprietary. Broadly, hearing aids use acoustic features to estimate the probability that a given sound belongs to one of six possible classes: quiet, speech, noise, music, machine, or wind. The amount of time within each snapshot that each hearing aid returned a classifier was recorded. Classifier values were averaged between the left and right hearing aids within each snapshot. Then, the distribution of classifiers was analyzed.

To characterize the effect of location and subject group on hearing aid feature activation, directional microphone activation and gain reduction were analyzed. For each snapshot, the amount of time within the snapshot each hearing aid was in directional mode was recorded. The hearing aids entered directional mode when the level exceeded an estimated 60 dB SPL and noise was detected, although the exact heuristics of directional mode activation are proprietary. Directional mode transition occurred over 5 s. If the hearing aid was in omnidirectional mode, 0 was reported, and if it was in directional mode, 1 was reported. If the state was transitional, a value between 0 and 1 was reported. Directional microphones were considered to be activated if at least one of the two hearing aids was in directional mode (>0.5 state) for more than half of the data points within the snapshot. Finally, gain reduction, a type of digital noise reduction, was analyzed. The hearing aids applied gain reduction within a channel when noise was dominant in that channel. For each snapshot, the mean amount of gain reduction in each of the 24 channels for each hearing aid was recorded (in dB). Gain reduction across all 24 channels was averaged. Differences in gain reduction between left and right hearing aids were analyzed, but the differences were small, and thus gain reduction was averaged between hearing aids. Then, gain reduction was analyzed as on or off. Gain reduction was considered if the average gain reduction exceeded 2 dB during the snapshot, based on prior work with similar hearing aids (Bentler et al. 2008).

Ecological Momentary Assessment

In addition to hearing aid data, participants completed EMA (during EMA-associated snapshots). EMAs are in-situ surveys designed to capture information about the participant's perceptions of and experiences in a listening environment in near real-time, providing data with high context resolution and low-recall bias (Shiffman et al. 2008; Wu et al. 2020). The AudioSense+ app is a smartphone application designed for collecting data about listening environments by delivering EMAs to the participant in their daily life (Hasan et al. 2013; Wu et al. 2015).

Participants were trained to use the research Samsung Galaxy 6 smartphone and AudioSense+ app. Training for the smartphone included a demonstration of the survey using a demo feature built into the app, and a demonstration of toggling between ring and vibration mode, charging, and powering on and off the phone. The phone was locked such that participants could only access the AudioSense+ app and no other features or apps on the phone. Participants were alerted to a survey delivery with an auditory alarm or a vibration, depending on their preference. During the week, participants were alerted to complete a survey approximately every 40 minutes (±5 minutes, varied randomly), and participants could not initiate an EMA themselves. Forty minutes with a 5-minute random factor was chosen to collect as much data as practical. If a connection between hearing aids and smartphones could not be established, the survey was skipped.

The EMA asked participants to report on their listening environment during 5 minutes before the delivery of the survey. Questions relevant to the present study were listening activity (what the participant was listening to), and how loud the background noise level was (Table 1). For the complete survey, see Wu et al. (2021).

ALDQ

Finally, participants completed a retrospective questionnaire the ALDQ (Gatehouse 1999). The ALDQ comprises 24 items, each describing a listening situation. Participants completed the ALDQ during Visit 2 and were asked to answer the questions with respect to the previous week. The participant selects how often they encounter each situation (very rarely/sometimes/often) as well as how important each situation is (very little/some importance/very important). An overall score is calculated by summing the products of the frequency and importance of each item. The total score is reported as a percentage. Higher scores are assumed to indicate more diverse auditory environments.

Analysis

All analyses were done in R 4.0.5 (R Core Team 2021). For data with repeated measures, most analyses were performed using mixed-effects models with random intercepts for participants using the *lme4* package (Bates et al. 2015). For more information regarding the use of mixed-effects models for hearing and EMA research, the interested reader is pointed to Oleson et al. (2019a), Oleson et al. (2019b), Schielzeth et al. (2020), and Oleson et al. (2022). As this study was interested in group differences, rather than differences from a reference level, a priori pairwise contrasts with false discovery rate adjustments were performed after each regression (Glickman et al. 2014). Pairwise comparisons were computed using the *emmeans* package (Lenth 2021). To compute p values for pairwise comparisons, t-tests with Kenward-Roger approximations for degrees of freedom were used for linear mixed-effects models and Z-tests with infinite degrees of freedom were used for logistic mixed effects models. Raw effect sizes, either in mean differences (for normal linear mixed models) or odds ratios (for logistic mixed models) are reported where applicable. Where appropriate, one-way analysis of variance (ANOVA) and Pearson correlations were also performed, as noted in the results, using base functions in R. The linear mixed-effects assume the residuals are approximately normally distributed while the random intercept captures within-subject correlation. Model assumptions were evaluated by visually examining the residuals, and no evidence of violating model assumptions was detected.

TABLE 1. Relevant EMA questions and response options.

EMA Questions and Response Options	
Question	Response
Were you actively listening most of the time?	Yes
	No
What did your active listening involve? (select all that apply)	Conversation, live
	Conversation, electronic device
	Speech/music listening, live
	Speech/music listening, media
	Environmental sounds listening
Overall, how loud were the background sounds?	Very loud
	Loud
	Medium
	Soft
	Very Soft

EMA, ecological momentary assessment.

RESULTS

Compliance

A total of 8412 snapshots were recorded by the hearing aids of the 46 participants (1668 for YNH-U, 2133 for OHL-U, 1870 for YNH-R, 2741 for OHL-R). Average daily hearing aid use time (read from the data-logging report in the hearing aid fitting software) was available for a subset of participants from the rural group (7 from the YNH-R group and 12 from the OHL-R group). These data were used to estimate the number of snapshots collected per hour, as it is known that data can be lost when a stable Bluetooth connection between the hearing aids and smartphone is not detected. Among the YNH-R participants for whom data were available, the average daily hearing aid use time was 8.71 hours (SD = 1.41 hours), and snapshots were collected, on average, every 20.38 minutes. Among the OHL-R participants for whom data were available, the average daily hearing aid use time was 13.17 hours (SD = 1.51 hours), and snapshots was collected, on average, every 27.1 minutes. For this subset of participants, the OHL-R group wore their hearing aids for more hours during the day than the YNH-R group ($t(13.45) = -6.46$, $p < 0.001$). Because the OHL-R group were hearing aid users and wore their hearing aids longer than the YNH-R group, they likely wore their hearing aids before and/or after the window of snapshot collection each day. Thus, the actual snapshot timing interval for the OHL-R group is likely shorter than 27 minutes. The number of snapshots collected per participant did not differ between groups ($t(8.69) = -0.77$, $p = 0.459$).

Among all snapshots, 2667 were EMA-associated snapshots. On average, each participant completed 8.3 EMA surveys per day (7.8 for YNH-U, 8.9 for OHL-U, 5.6 for YNH-R, and 9.9 for OHL-R). To estimate EMA compliance, the EMA app tracked and calculated the survey completion rate. Because this feature was added to the app later in the study, the compliance data were not available for all participants. On the basis of the compliance data from 10 subjects, compliance was high (75.8%) (Wu et al. 2021). Among the 2667 EMA-associated snapshots, 1861 were snapshots where the participants indicated they were actively listening (based on Question 1 shown in Table 1) (453 for YNH-U, 531 for OHL-U, 254 for YNH-R, and 623 for OHL-R). A separate analysis of hearing aid data using only the EMA-associated, active listening snapshots was performed, but there were no major differences from using the full set of snapshots (i.e., EMA-associated and non-EMA-associated combined). Therefore, all snapshots for hearing aid data are reported. Unless otherwise noted, each analysis used the full sample size of snapshots. Boxplots showing the distribution of the number of snapshots per participant for each group for all snapshots and EMA-associated, active listening snapshots are shown in

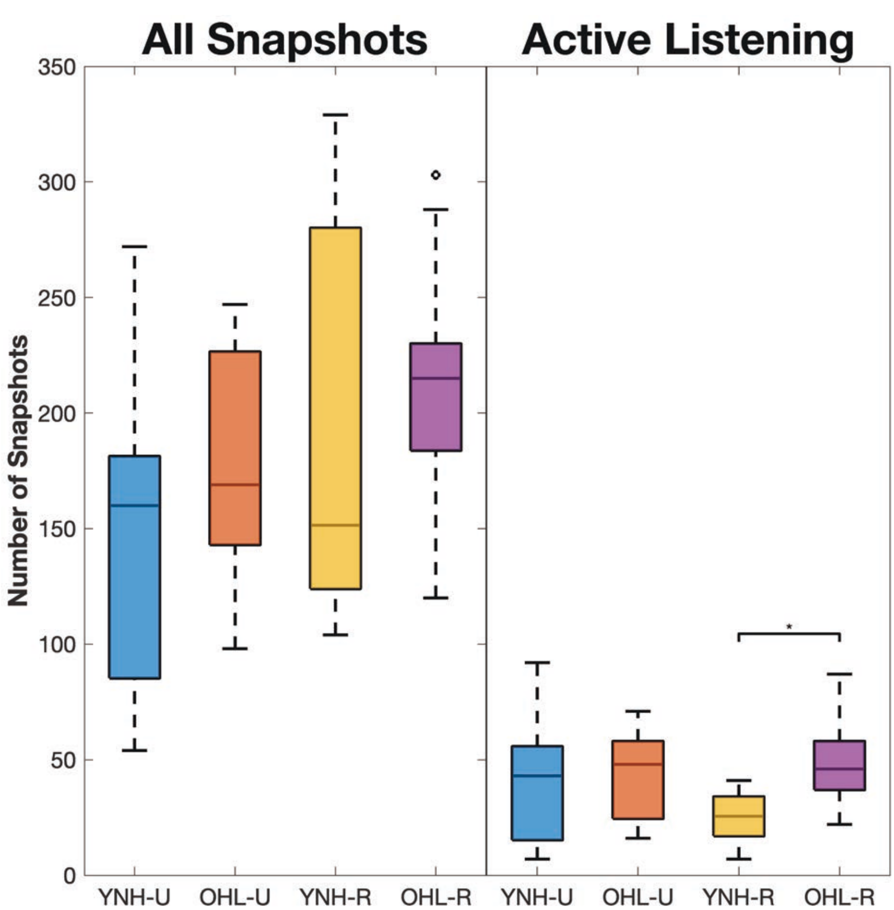

Fig. 2. Number of snapshots per participant for each group for all snapshots (left) and EMA-associated, active listening snapshots (right). Horizontal bars represent median values. Vertical bars represent values within the first and third quartiles ± the interquartile range × 1.5. Dots represent outliers. Brackets with stars indicate significant differences ($p<0.05$). OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

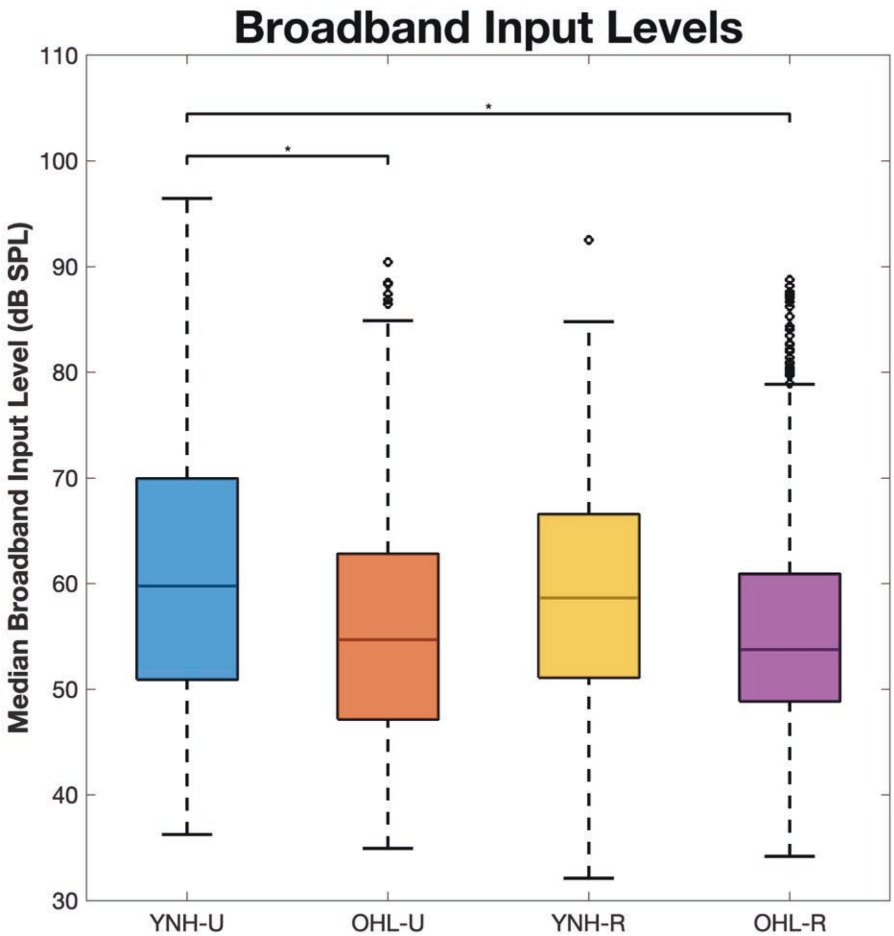

Fig. 3. Median broadband input levels averaged between left and right hearing aids. Input level is in dB SPL. Horizontal bars represent median values. Vertical bars represent values within the first and third quartiles ± the interquartile range × 1.5. Dots represent outliers. Brackets with stars indicate significant differences (p<0.05) OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

Figure 2. ANOVA showed that the total number of snapshots did not differ significantly between groups ($F(3) = 1.779$, $p = 0.166$). For EMA-associated, active listening snapshots, the YNH-R collected, on average, 22 fewer surveys than the OHL-R group ($t(42) = -2.837$, adjusted $p = 0.042$).

Median Broadband Input Level

Median broadband input levels in dB SPL for all snapshots for all groups are shown in Figure 3. In general, the YNH groups had higher input levels than the OHL groups, and the rural groups had lower median levels than their matched urban group, but most differences were not statistically significant. Pairwise contrasts (with false discovery rate corrections) from the linear mixed effects model are shown in Table 2. There were significant differences between the YNH-U group and OHL groups, with the YNH-U group having significantly higher median input levels than the OHL groups (model estimated 4.43 dB and 4.08 dB higher levels than the OHL-R and OHL-U groups, respectively). The difference between the YNH-R and OHL-R groups approached but did not reach significance (adjusted $p = 0.076$).

Variance of Broadband Input Levels

In addition to the median input level for each snapshot, the SDs of input levels *within* and *between* each snapshot were also analyzed. Within-snapshot SDs were computed by calculating the SD of samples within each snapshot for each hearing aid. There were no significant group differences for within-snapshot input level variance (see Supplemental Appendix, Table A1, Supplemental Digital Content 1, http://links.lww.com/EANDH/B72). The average within-snapshot broadband input level SD across groups was 3.2 dB.

Between-snapshot sound level variance among groups can be visualized by plotting the probability density functions of median broadband input levels for all groups (Fig. 4). Recall that the integral of the probability density function is 1, and therefore taller, more narrow probability density functions indicate higher predictability (i.e., less variance). Visually, the OHL-R group had a taller, more narrow probability density function than the other groups. To assess significant differences between groups for between-snapshot sound level variance, the SD of median broadband input levels was calculated within each participant. In short, this statistic indicates how much sound pressure levels varied between snapshot for each subject. Then, an ANOVA and pairwise contrasts with false discovery rate adjustments were used to assess significant differences in variance between groups. These results are shown in Table 3. Only the variance between the OHL-R and YNH-U groups was significant with a mean difference of 2.47 dB (adjusted $p = 0.008$),

TABLE 2. Pairwise contrasts between groups for median broadband input levels

Pairwise Contrasts: Median Broadband Input Levels						
Contrast		Mean Difference	SE	df	*t*	*p*
YNH-R	OHL-R	3.20	1.49	41.5	2.14	0.076
YNH-R	YNH-U	−1.23	1.56	42.6	−0.79	0.523
YNH-R	OHL-U	2.85	1.52	41.8	1.87	0.103
OHL-R	**YNH-U**	**−4.43**	**1.46**	42.4	**−3.03**	**0.025**
OHL-R	OHL-U	−0.35	1.42	41.4	−0.25	0.805
YNH-U	**OHL-U**	**4.08**	**1.49**	42.7	**2.73**	**0.027**

P values are adjusted with false discovery rate corrections. Bold = p < 0.05.
OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

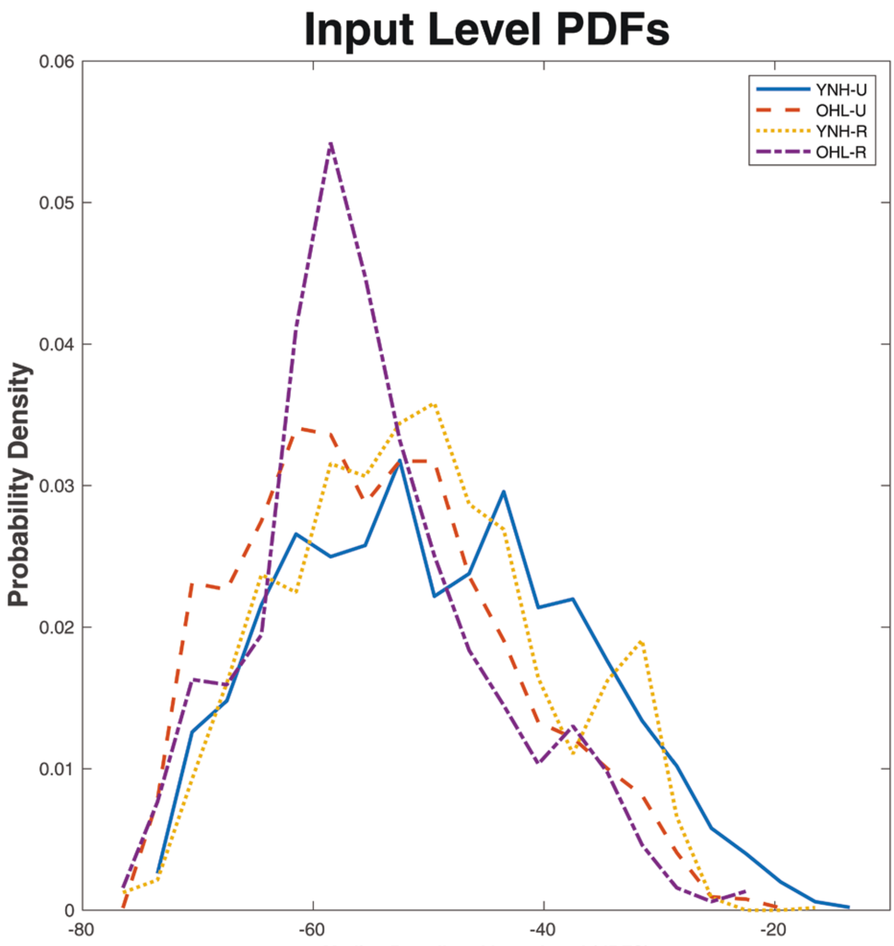

Fig. 4. Probability density functions showing the distribution of median broadband input levels. OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

TABLE 3. Pairwise contrasts between groups for between-snapshot broadband input level variance

Pairwise Contrasts: Between-Snapshot Variance of Broadband Input Levels						
Contrast		Mean Difference	SE	df	*t*	*p*
YNH-R	OHL-R	0.92	0.73	42	1.26	.323
YNH-R	YNH-U	−1.55	0.76	42	−2.03	.096
YNH-R	OHL-U	0.22	0.75	42	0.29	.771
OHL-R	**YNH-U**	**−2.47**	**0.71**	**42**	**−3.46**	**.008**
OHL-R	OHL-U	−0.70	0.70	42	−1.01	.383
YNH-U	OHL-U	1.77	0.73	42	2.43	.058

P values are adjusted with false discovery rate corrections. Bold = p < 0.05.
OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

although the difference between the YNH-U and OHL-U groups approached significance (adjusted $p = 0.058$).

Hearing Aid Sound Classification

Differences in the proportion of sound classifications within snapshots were analyzed to determine whether groups spent different amounts of time in different auditory environments. Hearing aids classified sounds into one of six categories: quiet, speech, noise, machine, music, and wind. Few snapshots contained machine, music, or wind; therefore, only quiet, speech, and noise were analyzed. It should be noted that noise and speech classifications can co-occur, and therefore the total classification proportion for a given snapshot may exceed 1. There were no significant differences among groups for any classification (see Supplemental Appendix Table A2, Supplemental Digital Content 1, http://links.lww.com/EANDH/B72). Quiet was the least recorded classification (mean = 28%, SD = 38%), followed by speech (mean = 30%, SD = 33%), and noise (mean = 48%, SD = 34%).

Directional Microphones

As expected, directional microphone activation followed a similar pattern as observed in the input level differences between groups. Proportions of snapshots with and without directional microphone activation for all groups are shown in Figure 5. The YNH-U group was more likely to have activated directional microphones than the OHL-R (adjusted $p < 0.001$) and OHL-U (adjusted $p = 0.011$) groups, and the YNH-R group was more likely to have activated directional microphones than the OHL-R group (adjusted $p = 0.011$) (Table 4). The effects were relatively large within each geographic group; the odds of directional microphone activation were 2.12 higher for the YNH-R group compared to the OHL-R group and 2.06 higher for the YNH-U group compared to the OHL-U group.

Gain Reduction

Group differences in hearing aid gain reduction activation were analyzed. Results were similar to the differences observed for directional microphone activation (Table 5). The YNH groups both had a significantly greater likelihood of gain reduction activation than the OHL-R group. The odds of gain reduction were 2.69 higher for the YNH-R than the OHL-R group and 2.86 higher for the YNH-U group than the OHL-R group.

Ecological Momentary Assessment

Listening activities, as recorded on EMAs, during survey-associated snapshots among groups were analyzed to determine whether the distribution of listening activities (Question 2 in Table 1) differed among groups. The distributions of the proportion of listening activities among groups are shown in Figure 6. For all groups, most listening situations comprised live conversation or passive listening to media. Generalized linear mixed-effect models with Bernoulli distributions and logit link functions were used to test whether groups differed

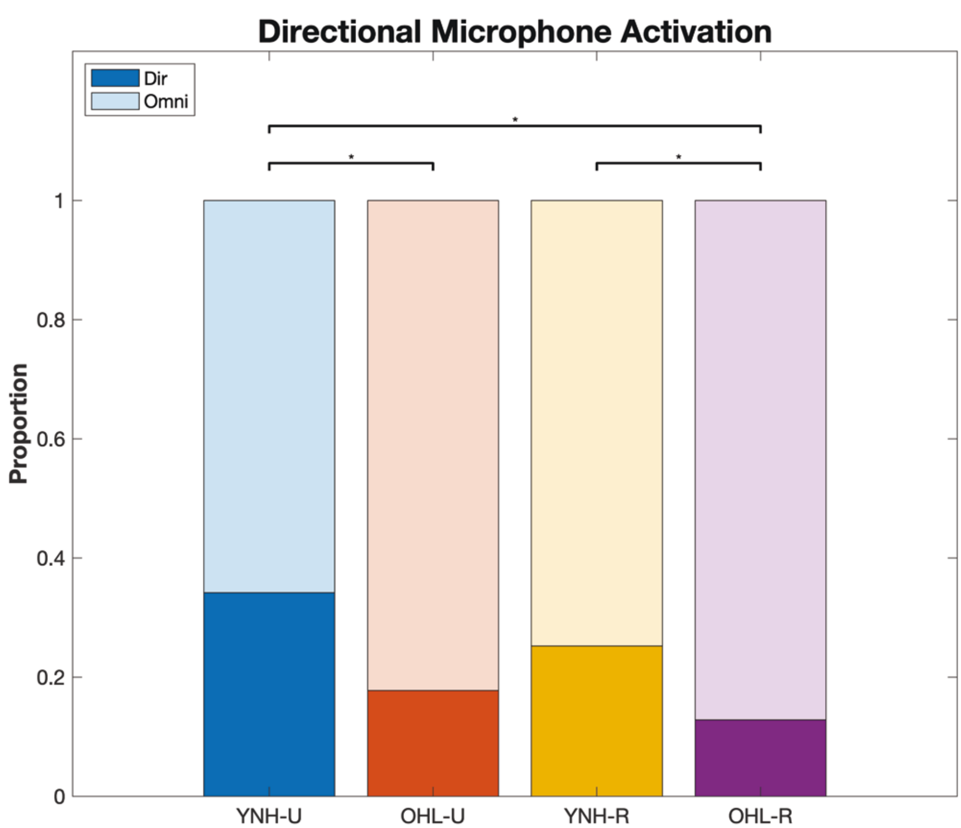

Fig. 5. Proportions of snapshots with directional microphone activation among groups. Darker shade on the bottom indicates directional microphone activation proportion and lighter shade on top indicates omnidirectional proportion. Brackets with stars indicate significant differences ($p<0.05$). OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

TABLE 4. Pairwise contrasts between groups for proportions of directional microphone activation

Pairwise Contrasts: Directional Microphone Activation					
Contrast		Odds ratio	SE	*z*	*p*
YNH-R	**OHL-R**	**2.12**	**0.56**	**2.88**	**0.011**
YNH-R	YNH-U	0.75	0.21	–1.04	0.298
YNH-R	OHL-U	1.55	0.42	1.65	0.148
OHL-R	**YNH-U**	**0.36**	**0.09**	**–4.03**	**<0.001**
OHL-R	OHL-U	0.73	0.18	–1.24	0.259
YNH-U	**OHL-U**	**2.06**	**0.54**	**2.76**	**0.011**

P values are adjusted with false discovery rate corrections.
Bold = p < 0.05.
OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

TABLE 5. Pairwise contrasts between groups for hearing aid gain reduction activation

Pairwise Contrasts: Gain Reduction Activation					
Contrast		Odds ratio	SE	*z*	*p*
YNH-R	**OHL-R**	**2.69**	**0.82**	**3.26**	**0.003**
YNH-R	YNH-U	0.94	0.29	–0.19	0.846
YNH-R	OHL-U	1.55	0.48	1.42	0.186
OHL-R	**YNH-U**	**0.35**	**0.10**	**–3.52**	**0.003**
OHL-R	OHL-U	0.58	0.17	–1.89	0.117
YNH-U	OHL-U	1.65	0.49	1.65	0.149

P values are adjusted with false discovery rate corrections.
Bold = p < 0.05.
OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

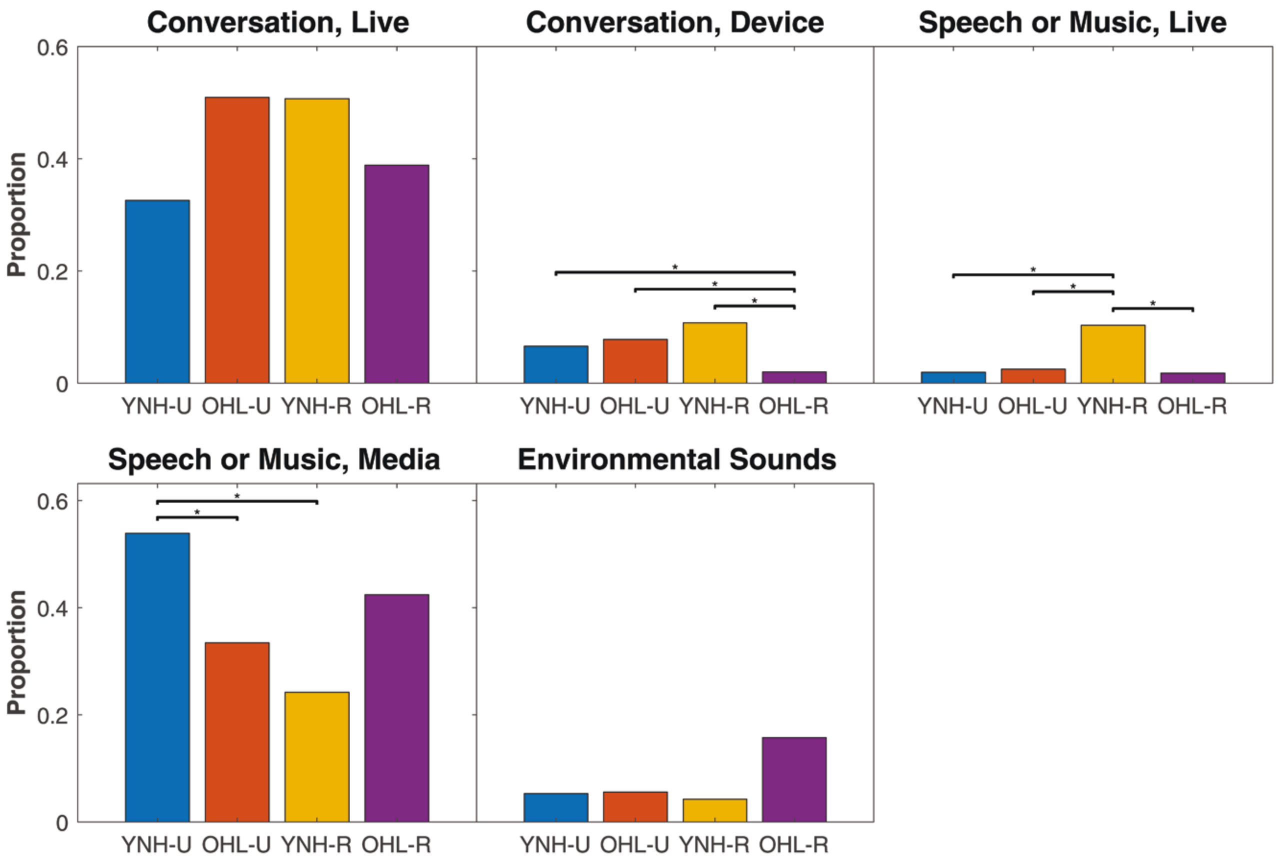

Fig. 6. Proportions of listening activities among groups during active listening snapshots. Brackets with stars indicate significant differences $p < 0.05$. OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

in the proportions spent in each listening activity (number of snapshots = 1249). There were no significant differences among groups for proportions of a live conversation or environmental sound listening. There were significant differences among groups for proportions of conversation on a device, live speech or music listening, and speech or music listening via media. The YNH groups were significantly more likely to have a conversation on a device than the OHL-R, but not the OHL-U groups. For example, the odds that the YNH-R group had a conversation on a device were 6.27 higher than the OHL-R group (adjusted $p = 0.006$), and the odds that the OHL-R group had a conversation on a device were 0.73 lower than the YNH-U group (adjusted $p = 0.045$). The YNH-R group had a greater proportion of listening to live speech or music than all other groups, with large effect sizes (OR = 5.18 to 8.93; adjusted $p = 0.012$ to 0.036). The YNH-U group had a greater proportion of listening to speech or music via media than the YNH-R (adjusted $p = 0.033$) and OHL-U (adjusted $p = 0.033$) groups, again with relatively large effects. Detailed statistics are available in Supplemental Appendix Table A3, Supplemental Digital Content 1, http://links.lww.com/EANDH/B72.

Ratings of background noise level (Question 3 in Table 1) were analyzed, where the effect of the group on the proportion of each response was tested using the same generalized linear mixed-effects model approach as listening activities (number of snapshots = 2074). There were no significant differences among groups within any noise level category (see Supplemental Appendix Table A4, Supplemental Digital Content 1, http://links.lww.com/EANDH/B72). For all groups, most listening environments had background noise levels rated as medium (mean proportion = 36%), soft (mean proportion = 27%), or very soft (mean proportion = 20%). Few environments comprised loud (mean proportion = 13%) or very loud (mean proportion = 3%) background noise levels.

Correlation between Environment and Hearing Aid Feature Activation

With the assumption that hearing aid features are activated by acoustic properties of the environment, a correlation analysis was performed between environment factors and hearing aid feature activation. To perform the correlation analysis, each factor was first averaged within the participants. Then, Pearson correlations were computed between environment measures and hearing aid feature activation. For Pearson correlations between EMA and hearing aid features, only the snapshots paired with EMA were included. The results are shown in Table 6. As expected, hearing aid feature activation was primarily driven by input level, with strong and significant correlations observed between feature activation and median input level. Between-snapshot input level variance was moderately correlated with directional microphone activation and gain reduction. Quiet environments were moderate to strongly correlated with hearing aid feature activation. The speech was moderately correlated with directional microphone activation, and the noise was correlated with both features. Background noise level rating, as reported on the EMA was moderately correlated with both directional microphone activation (on/off) and mean gain reduction.

Auditory Lifestyle and Demand

ALDQ scores for each group are shown in Figure 7. Although the OHL groups appeared to have higher scores (a more diverse auditory lifestyle), a one-way ANOVA showed no differences between groups ($F(3, 41) = 0.59$, $p = 0.622$). Further analysis showed that the higher scores observed for the OHL groups were driven by differences in the importance subscale; the YNH groups had importance scores that were on average 5.1 points (raw score) lower than for the OHL groups. Because the ALDQ is a retrospective questionnaire, rather than an in-situ measure as are all other metrics in this study, an additional analysis was performed to determine whether the ALDQ scores were correlated with any of the other measures of auditory environment collected in this study. Pearson correlations were analyzed between ALDQ scores and all other metrics, averaging repeated measures within-subject. The only significant correlation was a moderate correlation between the ALDQ and the proportion of speech recorded by the hearing aid scene classifier ($r = 0.339$, $p = 0.023$). All other correlation coefficients were low, between −0.031 (directional microphone activation) and 0.179 (within-snapshot input level variance), with an average correlation of 0.023.

DISCUSSION

The purposes of this study were to investigate whether location (urban versus rural), age, and hearing status (younger with normal hearing versus older with hearing loss) affected encountered auditory environments and hearing aid feature activation. We hypothesized that (1) urban dwellers and younger listeners would have more diverse and more demanding auditory environments than rural and older dwellers, respectively; and (2) hearing aid feature activation would follow environment differences, with greater feature activation for the urban dwellers

TABLE 6. Pearson correlation coefficients for soundscape characteristics and hearing aid feature activation

	Correlations between Soundscape and Hearing Aid Features						
	Hearing Aid						EMA
	Median Input Level	Between-Snapshot Input Level Variance	Within-Snapshot Input Level Variance	Quiet	Speech	Noise	Background Noise Level
Directional Microphones	**0.84*** **	**0.47** **	0.01	**−0.52*** **	**0.34***	**0.38***	**−0.44** **
Gain Reduction	**−0.79*** **	**−0.32***	0.09	**−0.54*** **	−0.27	**−0.36***	**−0.38** **

EMA, ecological momentary assessment.
Bold = p < 0.05.
**p < 0.05, **p < 0.01, ***p < 0.001.*

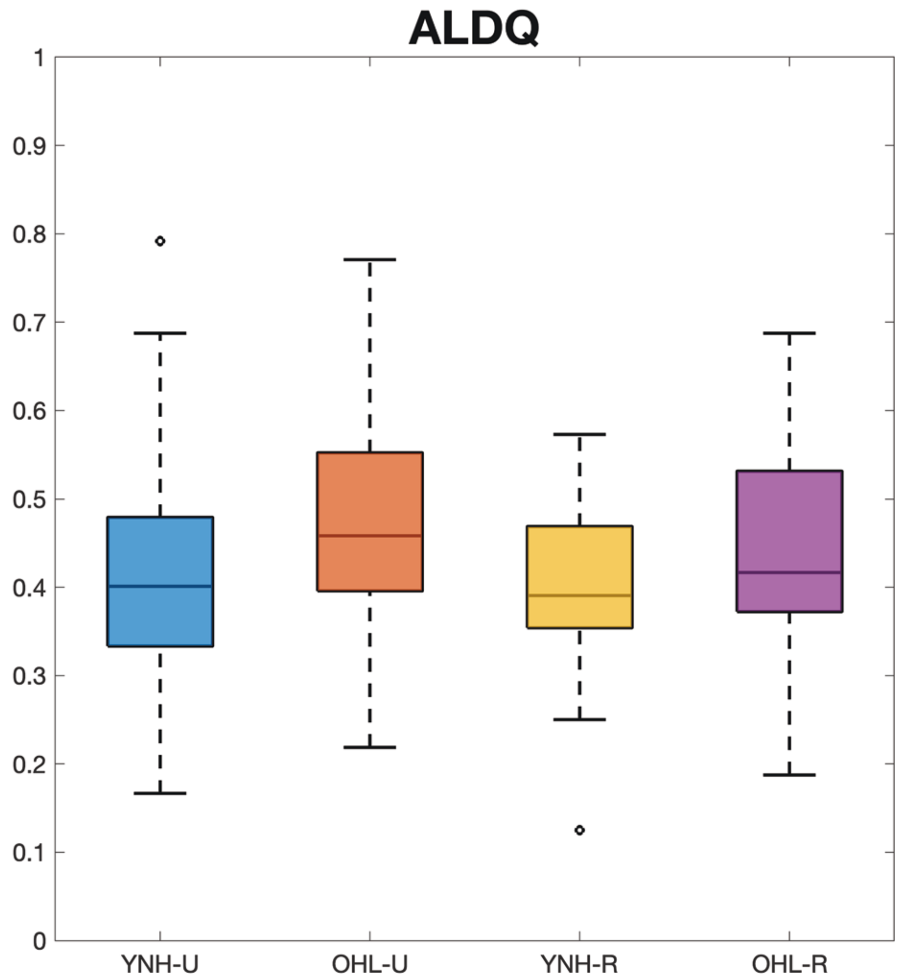

Fig. 7. ALDQ scores for all groups. Horizontal bars represent median values. Vertical bars represent values within the first and third quartiles ± the interquartile range × 1.5. Dots represent outliers. ALDQ, Auditory Lifestyle and Demand Questionnaire. OHL-R, older participants with hearing loss in a rural area; OHL-U, older adults with hearing loss; YNH-R, younger participants with normal hearing in a rural area; YNH-U, younger adults with normal hearing.

and younger listeners than the rural dwellers and older listeners, respectively.

The results offer mixed support for our hypotheses. The most consistent finding was that the YNH-U group had more demanding and diverse auditory environments and more hearing aid feature activation than the other groups—especially the OHL groups. The YNH-U group had significantly higher sound levels than the OHL groups (Fig. 3) and significantly larger between-snapshot variance in sound levels compared to the OHL-R group (Fig. 4). Overall, the YNH-U group had a median input level of an average of 5 dB higher than the OHL groups. The YNH-R group had sound levels between the YNH-U group and the OHL groups, without significant differences from any other group; however, this may suggest that how diverse or demanding auditory environments are tends to follow a gradient from younger, urban-dwelling listeners, to younger rural dwelling listeners, to older listeners. The hearing aid feature activation results generally followed environment differences, with the YNH-U group having a higher likelihood of directional microphone activation than the OHL groups (Fig. 5), and both YNH groups having a higher likelihood of gain reduction activation than the OHL-R group. It is important to note that the effect size of the difference in directional microphone activation was considerably larger for the difference between the YNH-U group and the rural groups than between the YNH-U and OHL-U group. Further, the effect size of the difference in gain reduction activation was larger between the YNH-U and OHL-R groups than between the YNH-R and OHL-R groups.

Taken together, these findings suggest that demographics may affect auditory environments and hearing aid feature activation. Although most of the results did not show significant differences between the YNH-U and YNH-R groups, it is telling that there were significant differences in many metrics between the YNH-U group and the OHL groups, but there generally were not differences between the YNH-R group and the OHL groups. This might suggest that the auditory environments of the YNH-R group were more similar to those of the OHL groups than the YNH-U group.

Sound levels found in this study were overall higher and more varied than those found by Christensen et al. (2021a,b). Using a similar method, these authors found a grand median SPL among 98 hearing aid users of 54.42 dB (SD = 6.68 dB). The grand median SPL in this study was 55.82 dB (SD = 11.27 dB); thus, we found a slightly higher median SPL and a larger variance. Although Christensen et al. did not have demographic data on their participants, they estimated that 6 of 10 of their participants were around 74 years of age. That we specifically included younger listeners, who we observed to encounter generally louder and more varied environments, may then account for the larger and more varied sound levels found in this study and offers further support that demographics may affect auditory environments.

Our results in terms of the proportions of auditory environments encountered by hearing aid users, as recorded using hearing aid sound classification, were somewhat in contrast with the hearing aid classification findings of Humes et al. (2018) and Andersson et al. (2021). In the current study, the mean proportions of hearing aid sound classification were 28% quiet, 30% speech, and 48% noise or speech-in-noise. Humes et al. (2018) reported very similar proportions for quiet and speech, with median proportions of approximately 31% for quiet and 29% for speech, but a lower proportion for speech or speech-in-noise, at about 38%. Andersson et al. (2021) found mean higher proportions of quiet (48%) and speech (37%), and a much lower proportion of noise or speech-in-noise (14%). A likely reason for this discrepancy, particularly with respect to the proportions of noisy environments encountered, is that the way hearing aids classify sounds differs among manufacturers and models. The algorithms used to classify soundscapes are proprietary, their accuracy varies considerably, and the types of inaccuracies vary from manufacturer to manufacturer (Groth & Cui 2017). Hearing aid classification has great promise in furthering our understanding of auditory environments among hearing aid users, but more work on the validity of hearing aid sound classification and its effectiveness in improving outcomes is needed.

The self-reported listening activity results are somewhat difficult to interpret (Fig. 6), in part due to the broad categories of activities used for the EMAs. The YNH-R group had significantly more conversations on a device than the OHL groups and significantly more live speech or music listening than all other groups. A reasonable interpretation is that the YNH-R group talked on the phone more than the OHL group, but the YNH-U group did not. The large difference in live speech or music listening between the YNH-R group and the other groups may be simply because some of the YNH-R participants were college students, and thus live speech may simply reflect time spent in lecture, although participants from all groups reported participation in classes of some kind where live speech listening might be expected. That the YNH-U group listened to significantly more speech or music on media than the OHL-U and YNH-R group may reflect a greater amount of time spent listening to music on a portable device or phone, or more time watching television or some combination of the two. From prior work (e.g., Klein et al. 2018), it seems likely that a considerable portion of media listening, at least among the OHL groups, came from television. Although it did not reach significance, the OHL-R group spent more time listening to environmental sounds than all other groups. Rural areas do have considerably higher levels of nature and animal sounds than urban areas (Joo et al. 2011), and perhaps this reflects that fact, although whether that is the case cannot be directly inferred from these data.

Significant differences were found in broadband input levels between some groups (Fig. 3), but not in the proportions of self-reported background noise levels on the EMA. To better understand this, we performed an analysis to assess the relationship between EMA responses (treated continuously) and broadband input levels. We found that, for all groups, ratings of background noise level varied with broadband median input level, with higher input systematically resulting in higher ratings of background noise level ($t(1859) = -19.63$, $p < 0.001$). Why then we did not observe differences between groups on the EMA responses is an important question. One possible reason is that the internal reference for self-report ratings varies based on demographics or lifestyle factors. Participants in all groups generally rated environments with higher sound levels as noisier and environments with lower sound levels as softer, but this was relative to the overall range of input levels experienced by each group. An additional factor is that participants with hearing loss also completed ratings of environments based on amplified sound through their hearing aids, which might affect the relationship between objective levels and ratings, although prior research suggests that hearing aid use does not generally affect perceptions of loudness or noisiness reported on EMAs (Jorgensen et al. 2021). A final possibility is that loud environments are under-sampled on EMA, as participants may be more likely to skip surveys delivered in louder environments (Schinkel-Bielefeld et al. 2020; Wu et al. 2021). How objective and subjective measures of sound level relate warrants further investigation. It is not immediately clear how to best match these two types of data.

Clinical Implications

Our findings generally support prior work showing that older adults have less diverse and demanding listening environments than younger adults (Wu & Bentler 2012; Humes et al. 2018; Klein et al. 2018; Wu et al. 2018). Coupled with the findings of Gatehouse et al. (2006b) and Christensen et al. (2021a,b), our findings suggest that older adults with hearing loss could potentially exhibit different patterns of benefit or preferences for hearing aid fittings than younger adults with hearing loss. The lack of real-world effectiveness of premium hearing aids and advanced hearing aid features among older adults was found by Wu et al. (2019) may in part be because older adults are often not in auditory environments where benefits from these technologies could be consistently observed.

Prior studies investigating the auditory environments of hearing aid users have included participants in primarily rural areas, and the findings might not reflect older listeners in more urban environments (Humes et al. 2018; Klein et al. 2018; Wu et al. 2018). The current study did not find significant differences between the sound levels or self-report background noise levels between the OHL groups; however, the sound levels and background noise levels were consistently lower for the OHL-R group than the OHL-U group. We also showed that directional microphone activation was more likely for the YNH-U group than other groups, with a larger effect size between the YNH-U and OHL-R group than between the YNH-U and OHL-U group, suggesting rural populations may not encounter as many environments where hearing aid features are activated as urban populations. Recent studies showing a lack of effectiveness of hearing aid features and audiology best-practice interventions (Humes et al. 2017; Wu et al. 2019) may then not generalize to all populations. The lack of hearing aid feature effectiveness in the real-world may also be due in part to the heuristics used to control hearing aid features being inadequate in detecting and responding to difficult environments. We found that hearing aid feature activation was most strongly correlated with the overall input level of the hearing aid, with only weak-to-moderate correlations with input level variance, sound classification, and self-report of noise levels (Table 6).

Clinicians often assess the lifestyles of patients to inform hearing aid technology recommendations and fitting. Clinical assessments usually involve informal interviewing or the use of a questionnaire such as the ALDQ. The current found no differences between any of the groups on the ALDQ. Further, and consistent with prior work (Cox et al. 2011; Gatehouse 1999; Wu & Bentler 2012), the ALDQ was essentially not correlated with objective measures in the current study. The ALDQ may not be sensitive to real-world auditory lifestyle and demand. Retrospective questionnaires are subject to numerous biases that make them unreliable indicators of people's actual daily-life experiences, including poor recall of the frequency with which they encounter environments and their experiences in those environments (Shiffman et al. 2008; Wu et al. 2020). Non-auditory factors, such as health, education, and gender can also affect retrospective questionnaire scores (von Gablenz et al. 2018). Groups with objectively different auditory environments may have different internal references when subjectively reporting their experiences on the ALDQ. For example, we found that the noise level threshold for what constitutes a noisy situation may be higher for the YNH-U group than the OHL-R group. More sensitive clinical tools for assessing the auditory lifestyles of hearing aid users may enable better clinical decision-making when recommending and fitting hearing aids.

Limitations

Our findings cannot show whether the observed differences are due to age or hearing loss, as there were neither younger hearing loss groups nor older normal hearing groups included in this study. This is an important consideration for future studies. The definitions of urban and rural used in the current study were broad. Although it is true that Iowa City and the surrounding area are substantially more rural than the Berkeley area, there is urban, suburban, and rural overlap in both areas. We also only included two locations; the extent to which auditory environments share similar features between different cities or different rural areas is unknown.

Data were lost due to non-compliance and the technical limitations and reliability of Bluetooth. It is unknown whether Bluetooth connections were dropped in a random or systematic way. On the basis of available data, snapshots were, on average, collected approximately every 20 minutes rather than every 10 minutes, as the devices were intended to do. It is also unknown whether data are missing because of different amounts of hearing aid use time among participants. The data-logs that were available for some participants in the rural groups were analyzed and, although the OHL-R group used their hearing aids for more hours each day than the YNH-R group, the total number of snapshots collected did not differ between groups. We also do not have complete EMA compliance data for these participants. That is, we do not know the rate of skipping or ignoring surveys, although a prior study on 10 of the participants in this study found high compliance. As this type of technology improves, data with fewer missing points will be able to be collected in a more reliable manner.

Because the devices were programmed to collect sound levels throughout the day, we believe these data are reasonably representative. However, we do now know if comparing the overall mean sound level is the best indicator of differences in auditory environments between groups, as there could be fluctuations in sound level throughout the day (Christensen et al. 2021a,b). In future work, additional analysis techniques could be implemented to identify how patterns of auditory environments encountered over time differ between groups.

The ground truth for auditory environments or lifestyles typical of either Berkeley or Iowa City, and how representative our participant populations were of urban and rural locations more broadly, is unknown. We did not attempt to specifically target a culturally or lifestyle-diverse sample, and most participants were simply volunteers who heard about the study. Better understanding how lifestyle, cultural, and additional demographic factors moderate any effect of location or age on auditory environments is a critical area of research. Finally, the sample size was relatively small and the data collection period per participant was relatively short. One week of data collection is the average trial period for EMA studies across fields, and this the current study used more per-day assessments than the average number of six (Wrzus & Neubauer 2022). Further, the sampling period was longer than in prior work that has quantified the "auditory reality" of hearing aid users (e.g., von Gablenz et al. 2021). However, 1 week may be shorter than the average EMA sampling period used in audiology research, which is approximately 19 days (Holube et al. 2020). Whether the sample size and study length were sufficient to estimate the "true" auditory ecology of a listener or group is unknown. Future studies should determine how many listeners, how many samples, and how long of a study duration it takes to adequately and accurately represent the auditory environments of different listener groups.

CONCLUSIONS

Demographics affect auditory environments and hearing aid feature activation, with younger urban dwellers having the most diverse or demanding auditory environments and the highest frequency of hearing aid feature activation, and older, rural dwellers with hearing loss having the least diverse or demanding auditory environments and lowest frequency of hearing aid feature activation. However, the effects of location between younger listeners and older listeners are less clear, and additional research in this area is required. Future studies of the real-world auditory environments encountered by hearing aid users and audiologists' intervention effectiveness should consider location in the recruitment and interpretation of results.

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E.J. and Y-H.W. analyzed the data and wrote the article. J.X., Y-H.W., and J.G. designed the experiments and oversaw data collection. O.C. oversaw software and hardware used in data collection. J.O. oversaw statistical methods and data analysis. All authors discussed the results and implications and commented on the article at all stages. The following people provided support, assistance, and feedback at various points in the project: Michelle Jones, Sieon Kim, Shareka Pentony, Elizabeth Stangl, and Elizabeth Walker. Special thanks to those who participated in this research.

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