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ORIGINAL ARTICLE

GPS predicts stability of listening environment characteristics in one location over time among older hearing aid users*

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ABSTRACT

Objective: Hearing aid technology can allow users to "geo-tag" hearing aid preferences using the Global Positioning System (GPS). This technology assumes that listening environment characteristics that affect hearing aid benefit change little in a location over time. The purpose of this study was to investigate whether certain characteristics (reverberation, signal type, listening activity, noise location, noisiness, talker familiarity, talker location, and visual cues) changed in a location over time.

Design: Participants completed GPS-tagged surveys on smartphones to report on characteristics of their listening environments. Coordinates were used to create indices that described how much listening environment characteristics changed in a location over time. Indices computed in one location were compared to indices computed across all locations for each participant.

Study sample: 54 adults with hearing loss participated in this study (26 males and 38 females; 30 experienced hearing aid users and 24 new users).

Results: A location dependency was observed for all characteristics. Characteristics were significantly different from one another in their stability over time.

Conclusions: Listening environment characteristics changed less over time in a given location than in participants' lives generally. The effectiveness of GPS-dependent hearing aid settings likely depends on the accuracy and location definition of the GPS feature.

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Hearing aids; hearing aid outcomes; listening environment; soundscape; global positioning system

Introduction

Many devices and applications use the Global Positioning System (GPS) to control the device's behaviour, provide location-specific information to the user, or perform other location-based functions. Some hearing aids allow the user to adjust the volume and feature settings to optimise them for a certain location and then "geo-tag" those settings with the GPS coordinates of that location (e.g. Starkey Hearing Technologies 2018). When the user returns to that location, the hearing aid can automatically adjust to the settings previously selected by the user in that location. These technologies assume, however, that characteristics of listening environments that might affect hearing aid preferences or benefit remain relatively stable (or the same) over time. Presumably, when a hearing aid user chooses specific settings in a certain listening environment, they do so based on characteristics – acoustic and otherwise – of that listening environment. For geo-tagged hearing aid settings to be preferred by the user and provide consistent benefit in that location at various times, the listening environment characteristics of that location would need to remain relatively stable over time. That is, if the user chooses hearing aid settings in a given listening environment based on the characteristics of that environment at that time, the characteristics of that listening environment would need to be similar when the user returns to that environment at a later time for the geo-tagged settings to be appropriate. Whether this is the case or not is unknown. The purpose of this study was to investigate whether listening environment characteristics that might influence hearing aid preferences and benefit change in one location over time (see definition of the location used in this study below). To do this, eight listening environment characteristics that have been shown to affect hearing aid preferences or benefit were identified: reverberation, signal type, listening activity, noise location, noisiness, talker familiarity, talker location, and access to visual cues. These eight characteristics came from the larger study from which the data for the present study was taken. These characteristics are not exhaustive; there are many additional characteristics that might affect hearing aid preferences and benefit. These characteristics were chosen for their established impact on hearing aid preferences and benefit in the literature and their applicability to the most common listening environments. Each characteristic will be briefly reviewed with respect to its possible impact on hearing aid preferences or benefit.

Reverberation degrades speech perception for all listeners, but the effect is greater for listeners with hearing loss (Halling and Humes 2000; Harris and Reitz 1985; Xia et al. 2018). The negative effects of reverberation may be exacerbated by hearing aids as most modern hearing aids employ automatic gain control, which provides more amplification to lower-level sounds than higher-level sounds. In theory, such automatic grain control

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processing might provide greater amounts of amplification to reflected sounds than the original sounds, creating further smearing in the amplified signal. The degree of smearing in the signal may then vary depending on the amount of gain, expansion, and compression, as well as attack and release times, applied by the hearing aid. For example, speech intelligibility in reverberation is higher when compression release times are longer (Reinhart and Souza 2016).

The type of signal, particularly speech or non-speech, impacts hearing aid processing, preferences, and hearing aid benefit. In particular, hearing aids are poorer at reproducing music with high fidelity than speech (e.g. Chasin 2012; Chasin and Hockley 2014). For music listening, hearing aid users often prefer more linear gain, less aggressive features such as feedback management and noise reduction, larger input dynamic ranges, and more closed fittings (Chasin 2012; Leek et al. 2008; Madsen and Moore 2014). Relatively little is known about how hearing aid processing affects the perception of other sounds such as environmental sounds; however, it is plausible that hearing aid processing likely impacts how annoying hearing aid users find ambient noise or low-level environmental sounds (Vishnubhotla et al. 2012a, 2012b). For example, hearing aid users' preferences for expansion, which can reduce ambient and circuit noise particularly noticeable in quiet environments, differ depending on listening environment characteristics (Lowery and Plyler 2007).

Listening activity, such as small group conversation, larger group conversation, TV listening, or phone listening, likely also affects hearing aid preferences and benefits. Larger group conversation is more difficult than one-on-one or small group conversations for listeners with hearing loss, as switching among talkers disrupts speech perception in listeners with hearing loss (Kirk, Pisoni, and Miyamoto 1997). Hearing aid users may prefer adaptive directional microphones for group conversation, as adaptive directional microphones can adjust their polar plot based on the location of the signal (e.g. Ricketts 2000). However, benefit from and preference for directional microphones for group conversation likely depends on the location of the speaker relative to the listener, among other environmental characteristics (Gnewikow et al. 2009; Brimijoin et al. 2014; Walden et al. 2004). TV listening also differs considerably from listening in live conversation and may introduce many novel problems for listeners who use hearing aids (Gordon-Salant and Callahan 2009; Strelcyk and Singh 2018). How hearing aid users adjust their hearing aids for TV listening may depend on the type of program being watched and whether the hearing aid user is watching TV with others with normal hearing or hearing loss (Strelcyk and Singh 2018). Finally, speech perception for telephone listening varies as a function of how the phone signal is routed to the hearing aid, with wireless routeing and telecoil coupling resulting in better outcomes than acoustic coupling (Picou and Ricketts 2013). Hearing aid users may then prefer dedicated telephone programs to their primary settings for telephone listening. This may be similarly true for TV watching, as hearing aid preferences and benefits may depend on how the TV signal is routed to the hearing (e.g. through the hearing aid microphone versus streaming directly to the hearing aid).

Noise is the most exhaustively-researched listening environment characteristic, and it is well-known that greater amounts of noise have increasingly deleterious effects on speech perception, particularly for listeners with hearing loss (e.g. Bronkhorst 2000; Carhart and Tillman 1970; Dirks, Morgan, and Dubno 1982). Noise also impacts hearing aid preferences. Hearing aid users may prefer directional microphones in noisy environments, as directional microphones have been shown to improve speech perception in noise (e.g. Boymans and Dreschler 2000; Cord et al. 2002; for review, see Bentler 2005). Many hearing aid users may also prefer noise reduction features activated in noisy situations as it has been shown to improve comfort, sound quality, and listening effort (Bentler et al. 2008; Brons, Houben, and Dreschler 2013; Wong et al. 2018). Furthermore, younger hearing aid users who likely spend more time in noisy environments prefer faster-acting compression, presumably due to a higher rate and depth of time-domain amplitude modulations in noisy environments (Gatehouse, Naylor, and Elberling 2006). Taken together, these data indicate that hearing aid setting preferences likely vary as a function of the noise level in listening environments.

It is not merely the presence or level of noise that impact hearing aid preferences and benefit; the spatial orientation of the talker and the noise also plays a role. Directional microphones are designed to work and are more effective when the noise and signal have different source locations (e.g. Ricketts 2001). In quiet situations, hearing aid users may even prefer omnidirectional microphones, particularly when the talker is farther away. In noise, however, users do prefer directional microphones, but this preference may be predicated on the talker being relatively close and in front of the listener (Walden et al. 2004). Further, the spatial orientation of signals and noise have well-established effects on speech-in-noise perception independent of hearing aid technology. Namely, spatial separation of signals and noise generally improves performance, but this benefit may be reduced in listeners with hearing loss (Best, Mason, and Kidd 2011; Marrone, Mason, and Kidd 2008). In environments where the listener is uncertain where in space the signal and noise are coming from, such as in a group conversation in noise, performance is poorer than when the listener knows a priori where in space to attend to (Ericson, Brungart, and Simpson 2004; Kidd et al. 2005). Listeners can, however, adapt their listening strategies relatively quickly in environments where signal and noise orientation is uncertain and dynamic, resulting in improved performance (Brungart and Simpson 2007). Taken together, this work suggests that even in listening environments with similar levels of noise, the spatial orientation of the noise and the signal, as well as how dynamic the spatial orientation is, might have differential outcomes on hearing aid preferences or benefit. Further, hearing aid preferences and benefit may change in a single listening environment based on listeners' abilities to adapt to the environment.

Information from other sensory modalities and which may vary with the listening environment has also been shown to impact hearing aid preferences and benefit. It is well known that access to visual cues improves speech perception generally (e.g. Erber 1975). Visual cues show particular benefits in noisy situations, though the amount of benefit may depend on the type of background noise and the hearing status of the listener (Bernstein and Grant 2009). Further, visual cues improve speech-in-noise perception not only by reinforcing linguistic representation of the signal but by improving listeners' attention to the signal (Maddox et al. 2015). These benefits of visual cues have implications for hearing aid benefit; when visual cues are present, hearing aid users benefit little from directional microphones regardless of the acoustic properties of the environment (Wu and Bentler 2010). Hearing aid users also have better speech-in-noise perception when they are familiar with the talker (Souza et al. 2013). This phenomenon can result from implicit training, such as commonly occurs in the real world when listeners become familiar with a talker's voice through natural exposure over time (Kreitewolf, Mathias, and von Kriegstein 2017). Further, high familiarity with a talker's voice, such as that of a spouse, can aid not only a listener's ability to attend to the familiar voice among competing talker's but also to ignore the familiar voice in order to attend to an unfamiliar talker (Johnsrude et al. 2013). Hearing aid preferences and benefit may then fluctuate depending on whom the hearing aid user is listening to or attempting to ignore.

Taken together, this research indicates that hearing aid preferences and benefit likely depend on a number of listening environment characteristics. The present study was interested not in how these characteristics affected hearing aid preferences or benefit, but in whether they changed over time, and therefore if settings chosen in a listening environment at a given time by a hearing aid user would be expected to be the same settings chosen or yield the same benefit in that same location at a later time. Little is known about whether listening environments change over time. Hearing aid users do encounter a wide variety of listening environments generally (Jensen and Nielsen 2005; Klein et al. 2018; Smeds, Wolters, and Rung 2015; Wagener, Hansen, and Ludvigsen 2008; Wu and Bentler 2012). This varies for different listeners; some listeners encounter similar listening environments in more than half of their listening situations, while others encounter much more variety (Jensen and Nielsen 2005). Of particular relevance to the present study is the fact that even listening environments of the same classification seem to exhibit widely variable characteristics. For example, sound pressure levels can vary by as much as 40 dB in noisy environments and 20 dB in quiet environments (Smeds, Wolters, and Rung 2015; Wagener, Hansen, and Ludvigsen 2008). Even in listening situations at home, signal-to-noise ratios can vary by more than 15 dB (Wu et al. 2018). Furthermore, a variety of listening activities can occur in the same listening environment. For example, Wagener et al. found that conversation between two people, group conversation, and no conversation all occur frequently with housework (Wagener, Hansen, and Ludvigsen 2008). Wu et al. found that, although quiet situations with visual cues and the talker in front are most common, the availability of visual cues, talker location, and noise location all vary between both quiet and noisy situations (Wu et al. 2018). Taken together, these findings indicate either that listening environments of the same class vary considerably within that class, or that listening environments of the same class vary considerably over time.

The overall purpose of the present study was to determine how much the listening environment characteristics of hearing aid users changed in a given location over time. To that end, the primary research question of this study was: do listening environment characteristics change in a location over time, and, if so, how much? The secondary research question of this study was: do some listening environment characteristics change more in one location over time relative to others? To answer these questions, participants completed geo-tagged ecological momentary assessments (EMA) to report on listening events. These assessments asked participants about the eight identified listening environment characteristics that might affect hearing aid preferences. Participant responses were then used to calculate indices that captured the degree to which each of these characteristics varied in one location over time. Comparisons between location-specific and general stability indices were made to determine whether there was a location dependency on listening environment characteristics.

Methods

Design

This study was part of a larger, single-blinded, crossover study comparing the effect of hearing aid features in basic and advanced hearing aids (Wu et al. 2019). In the larger study, older adult participants with sensorineural hearing loss were recruited and fit with bilateral hearing aids. Each participant wore each of four hearing aid configurations (basic hearing aid with noise reduction features on and off, an advanced hearing aid with noise reduction features on and off) for 1 month. Some participants also completed an optional unaided condition. Upon completing the four conditions, most participants repeated one of the hearing aid conditions, selected randomly, to measure the reliability of their *in-situ* reporting. Each participant's involvement was 6–8 months. Each subject was also provided a Language Environment Analysis (LENA) device that recorded his or her auditory environment throughout the day as well as a smartphone to complete *in-situ* surveys. The focus of the current study was on the *in-situ* surveys and their relation to the location at which the survey was completed, as recorded by the smartphone.

Participants

Fifty-four older adults with hearing loss (26 males and 38 females ranging in age from 65–88 years with a mean age of 73.6 years) participated in this study. The participants were eligible for inclusion in the larger study if their hearing loss met these criteria: (1) postlingual, bilateral, sensorineural hearing loss (air-bone gap <10 dB at all audiometric frequencies); (2) four frequency (0.5, 1, 2, and 4 kHz) pure-tone average between 25 and 60 dB HL (ANSI 2010); and (3) hearing symmetry within 20 dB for all frequencies tested (0.25–8 kHz). These criteria were chosen based on the prevalence of this degree and configuration of hearing loss in the population (Lin et al. 2011), making this group reasonably audiometrically-representative of older adults with hearing loss. Audiometric data for participants is shown in Figure 1. All participants were native English speakers. All participants were recruited from eastern Iowa and western Illinois. Participants were primarily retired; one participant was employed full-time, seven were employed part-time, and the remainder were retired. Thirty of the participants were experienced hearing aid users (mean years of use = 8.5 years, standard deviation = 8.5 years). The remainder of the participants were new hearing aid users.

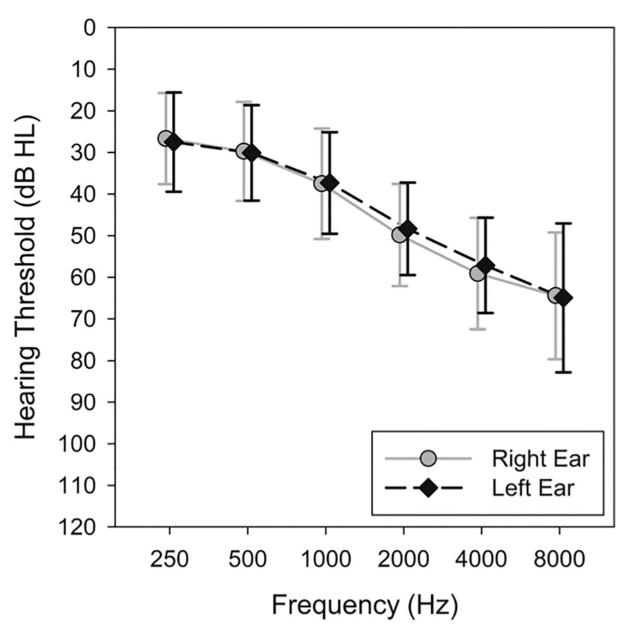

Figure 1. Mean audiometric thresholds and standard errors for all participants.

In-situ *survey*

Data about participants' listening environment characteristics were collected using EMA (Shiffman, Stone, and Hufford 2008). This methodology uses recurring self-report assessments to collect information about participants' listening experiences during or directly after those experiences. EMA addresses many of the limitations of traditional retrospective self-reports used in audiology by collecting information about the participant's listening experience in the real world and within minutes of the experience of interest, potentially giving researchers the ability to collect real-world data with high context resolution (information is collected *in-situ*) and low recall bias (little time elapses between the event and data collection) (Shiffman, Stone, and Hufford 2008). Hearing aid users have been shown to be accurate reporters of their listening environments using EMA (Wu et al. 2015).

In the present study, EMA was implemented through the use of smartphones (Samsung Galaxy S3). A custom application was designed for this study to deliver electronic surveys to participants (Hasan et al. 2013). The application prompted participants to complete surveys at pseudorandom intervals throughout the day, approximately every 2 h. Participants were able to specify time windows during which they were willing to be prompted for survey completion (e.g. after 8am and before 9pm). Participants were also encouraged to self-initiate a survey whenever they had a listening experience that they wished to report on. The surveys asked participants to answer questions about the listening environment they were in during the previous 5 min. Although participants were encouraged to complete the surveys during or right after the listening event, they were allowed to report the experience up to 1 h after the event.

In the EMA survey, participants were asked to respond to a question about each listening environment characteristic, apart from reverberation. The question related to each characteristic as well as the possible responses are shown in Table 1. All listening environment characteristics had representative questions on the EMA with response options that were categorical or ordinal. Rather than asking the participant to subjectively rate reverberation in the listening environment, which might be difficult for many hearing aid users, reverberation was estimated as high or low based on characteristics of the listening environment (listening location, room size, and carpeting). Specifically, outdoors and cars were assumed to be low-reverberant environments. In indoors, carpeted spaces that were equal in size or smaller than an average living room were considered to be low-reverberant environments. The remaining indoor locations were assumed to be high-reverberant (Walden et al. 2004). The survey was adaptive and skip patterns were implemented to tailor surveys for specific locations and activities. For example, if the participant indicated they were listening to speech, the survey would proceed to ask what type of speech listening activity they were

Table 1. Ecological momentary assessment questions and responses.

EMA Questions and Response Options

Question	Response
1. [Signal type] Were you listening to speech?	Yes
	No
1a. [Listening activity] (If "Yes") What were you listening to?	Conversation, 3 or fewer
	Conversation, 4 or more
	Speech listening, live
	Speech listening, media
	Conversation, phone
1b. [Listening activity] (If "No") What were you listening to?	Non-speech sound listening
	Not actively listening – (eliminated from analysis)
2. Where were you? (not included in analysis)	Outdoor/traffic
	Indoor
2a. [Location] (If "Outdoor/Traffic") Please be more specific.	Outdoor, moving traffic
	Outdoor, other than traffic
2b. [Location] (If "Indoor") Please be more specific.	Home, 10 or fewer
	Other than home, 10 or fewer
	Crowd of people, 11 or more
3. [Talker familiarity] (If listening to speech) Were you familiar with the talker(s)?	Unfamiliar
	Somewhat unfamiliar
	Somewhat familiar
	Familiar
4. [Visual cues] (If listening to speech) Could you see the talker's face?	No
	Yes, but only sometimes
	Almost always
5. [Talker location] (If listening to speech, but not on the phone), Where was the talker?	Front
	Side
	Back
6. [Noisiness] On average, how noisy was it?	Quiet
	Somewhat noisy
	Noisy
	Very noisy
7. [Noise location] (If not quiet) Where was the noise?	Front
	Side
	Back
	All around
8. (If indoor) Compared to an average living room, how large was the room?	Smaller
	About average
	Larger
9. (If indoor) Was there carpeting?	Yes
	No

Listening environment characteristic is in brackets. Parentheses indicate survey logic.

engaged in, whether they had access to visual cues, where the talker was located, and whether they were familiar with the talker. If the participant indicated they were not listening to speech, the survey would ask whether they were listening to non-speech sounds or not actively listening but would skip asking about visual cues, talker location, and talker familiarity. For the complete EMA survey, see Hasan et al. (2013). After the survey was completed, the answers and the latitude and longitude locations at which the survey was taken were saved on the phone. These data were uploaded to a server at regular follow-up appointments.

Procedures

This study was approved by the Institutional Review Board at the University of Iowa. After consenting to the study, participants completed a qualifying audiometric evaluation. If they met the criteria, participants completed a practice EMA condition. One week after completing the practice condition, participants were fit with hearing aids and instructed on the use of the audio recording devices and the smartphone. Once participants demonstrated competency on the use of the smartphone, they were sent home with the device and a set of written instructions for device use and care. Wi-Fi was enabled on smartphones to allow for more accurate location readings. Location accuracy on the phones was set to "high". For a complete description of procedures for the larger study, see Wu et al. (2019).

Data analysis

In total, participants completed 14,770 individual surveys (range completed between participants: 55–428; mean completed by participants: 206). Of these, 1813 were excluded from analysis because they were participant-initiated surveys in which the participant indicated that they were not reporting on a current listening event. That is, because participants had the option to initiate a survey and report on a listening event after the event had occurred, it could not be confirmed that the responses to these surveys reflected the participant's environmental conditions at the location in which the survey was completed. An additional 1802 surveys were excluded because they were completed in the practice condition. 3641 surveys were excluded because they did not contain GPS coordinates, either the result of the phone not being able to accurately record the GPS coordinates or other technical problems with the app, the phone, the internet or cellular connection, or the GPS satellites. After excluding these surveys, 7,514 surveys were included in the final analysis.

For the purposes of this study, data were collapsed across hearing aid conditions, including the unaided condition. This was done primarily because the question of interest in this study was whether characteristics of listening environments change over time, not whether there is an effect of hearing aid technology level or features on the perception of listening environment characteristics. Furthermore, among the listening environment characteristics evaluated in this study, all but one were unlikely to be affected by hearing aid use, technology level, or activated features. That is, how participants responded to questions about the listening situation, reverberation (which was calculated based on room size and carpet presence, rather than a subjective impression), signal type, listening activity, noise and talker location, access to visual cues, or talker familiarity would be unlikely to depend on hearing aid use, technology level, or activated features. It might be argued that participants in the unaided condition might have poorer reporting accuracy for some characteristics, particularly noise and talker location. However, it is not clear that hearing aids improve localisation (Akeroyd 2014; Denk, Ewert, and Kollmeier 2019). It might further be suggested that hearing aid use may affect listening activity, but prior research on these participants suggests that this is not the case (Klein et al. 2018). One characteristic, noisiness, may be affected by hearing aid condition. Therefore, to justify collapsing noisiness across conditions, the effect of hearing aid condition (including unaided) on noisiness rating was tested using a linear mixed-effects model with random intercepts for subjects and a Poisson distribution. An omnibus test using ANOVA showed no significant differences for noisiness between hearing aid conditions ($F(10) = 7.06$, $p = 0.71$). Conditions were therefore collapsed.

GPS coordinates were recorded continuously throughout the survey period. For this study, the first GPS coordinate recorded was used (GPS coordinate at survey prompt). Because the survey asked participants to report on the prior 5 min, it is possible in some instances that the GPS coordinates recorded at the start of the survey did not align perfectly with the GPS location during the 5 min prior. An assumption of this study was that the participant had not travelled far during the 5-min period between the listening event being reported on and the time of the survey. Because the present study was interested in using GPS to determine if listening environment characteristics remained constant in the same location over time, it was necessary to create a working definition of "same location" with respect to latitude and longitude. Generating such a working definition is complicated by the lack of verified accuracy for smartphone location data. Smartphones rely on mobile-station assisted-GPS (A-GPS), which uses a combination of the smartphone's cellular network and Wi-Fi connection in conjunction with the phone's GPS antenna to improve location accuracy and reduce locating time (LaMance, DeSalas, and Jarvinen 2002). However, due to the proprietary nature of the exact methods used, it is difficult to determine the exact accuracy of smartphone location measurements. Research on older devices (iPhone 3, Motorola, Sanyo) revealed location accuracy to be within 5–9 m outdoors and 11–21 m indoors (Zandbergen 2009; Zandbergen and Barbeau 2011). Newer devices have been shown to be accurate within 4.9 m under the open sky (van Diggelen and Enge 2015). For this study, a criterion level of 10 m was used for "same location". A 10-m criterion seemed to have reasonable face validity as a working definition of "same location" while accounting for the limits of A-GPS accuracy.

To calculate distances between survey locations, inter-point distances were measured between the coordinate pairs on all surveys using the Haversine formula to calculate the great-circle distance of all points from a common reference (Robusto 1957). This allowed for an accounting of the curvature of the earth; however, some error is inherent in this calculation due to stochastic topography factors such as hills and valleys. Locations at which surveys were completed are shown in Figure 2.

Two comparisons were required to answer the two research questions in this study. First, how much each listening characteristic changed in a specific, GPS-tagged location was compared to how much that listening characteristic changed overall without respect to a specific, GPS-tagged location. This comparison was performed to determine whether listening environment characteristics were location dependent. Second, how much each listening environment characteristic changed over time was compared to how much all other listening environment characteristics changed over time. This comparison was performed to determine which characteristics were relatively more stable than others. To perform these comparisons, four calculations were required. Broadly, these calculations generated two sets of indices that represented the percentage of survey responses for each characteristic that was the same over time either in a specific location or in general, adjusted for the number of possible survey responses for that characteristic. The first two calculations gave location-specific stability indices and general stability indices for each listening environment characteristic; these indices quantified how much each characteristic changed over time in a specific location or generally, respectively. Then, because survey questions for each characteristic had different numbers of possible responses, and therefore different chance levels, an additional two calculations transformed the original stability indices into comparable location-specific stability indices (cLSI) and comparable general stability indices (cGSI) by taking into account the response chance level for each characteristic. This allowed for comparisons between characteristics to be made. All calculations were computed using surveys within each participant. Specifically, the four calculations performed were as follows:

1. For each survey, a location-specific stability index for each listening environment characteristic was calculated by dividing the number of responses that were the same for each characteristic by the total number of responses on surveys taken by that participant within 10-m of the reference survey. Surveys that were completed at a unique location (no other surveys taken within 10 m) were eliminated from the analysis, as no data about change over time in that location was therefore available (2199 surveys). A histogram of the number of surveys completed for each location-specific stability index is shown in Figure 3. The mean number of surveys per index was 11.57 surveys and the standard deviation was 16.22. The location-specific stability index indicates how little or how much each characteristic changed in one location over time. Other approaches to calculating a location-specific stability index are possible – for example, using cluster analysis based on distance from some GPS coordinates. However, the approach taken in this study was chosen because it is similar to how hearing aids would adjust settings based on the location of the hearing aid user.
2. For each survey, a general stability index for each listening environment characteristic was calculated by dividing the number of responses that were the same as the reference survey response for each characteristic by the total number of surveys taken by the participant over the course of the experiment. The general stability index indicates how little or how much each characteristic changed overall across listening environments without respect to location.
3. To compare stability indices, which were based on survey responses with differing numbers of possible responses, the indices had to be transformed to comparable stability indices in order to account for different chance levels. The location-specific stability indices were transformed into comparable location-stability indices (cLSI) by taking the location-specific stability indices, subtracting one divided by the number of possible choices for that characteristic (μ), then dividing the difference by one minus μ. For example, signal type had two possible responses, speech or non-speech. Therefore, 0.5 was subtracted from the location-specific stability index for signal type for each survey. This difference was then divided by $1 - 0.5$, or 0.5

$$\mathrm{cLSI} = \frac{\text{Location specific stability index} - \mu}{1 - \mu}$$

4. Step three was repeated for the general stability indices to create comparable general stability indices (cGSI).

$$\mathrm{cGSI} = \frac{\text{General stability index} - \mu}{1 - \mu}$$

Statistical analyses were performed using linear mixed effect models with random intercepts for subjects and fixed effects for stability indices. Least squares mean estimates for both cLSI and cGSI were generated and a priori pairwise comparisons were performed within the cLSI and the cGSI to compare indices. Paired two-sample *t*-tests were used to compare the cLSI to the cGSI. Stability index calculations were performed using custom functions generated in MATLAB (2018). Statistical analysis was conducted in SAS 9.4 using the PROC MIXED and PROC PLM procedures.

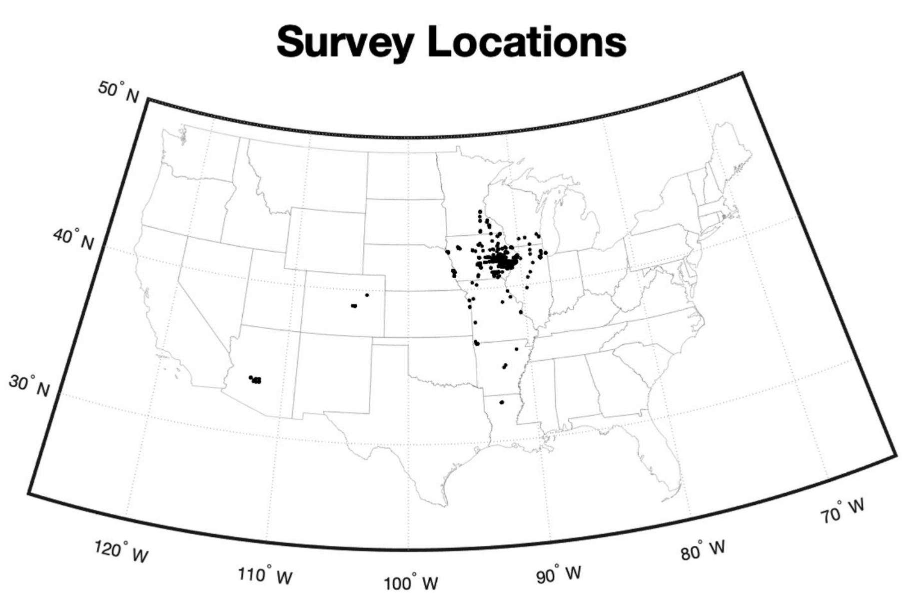

Figure 2. GPS coordinates of all ecological momentary assessments.

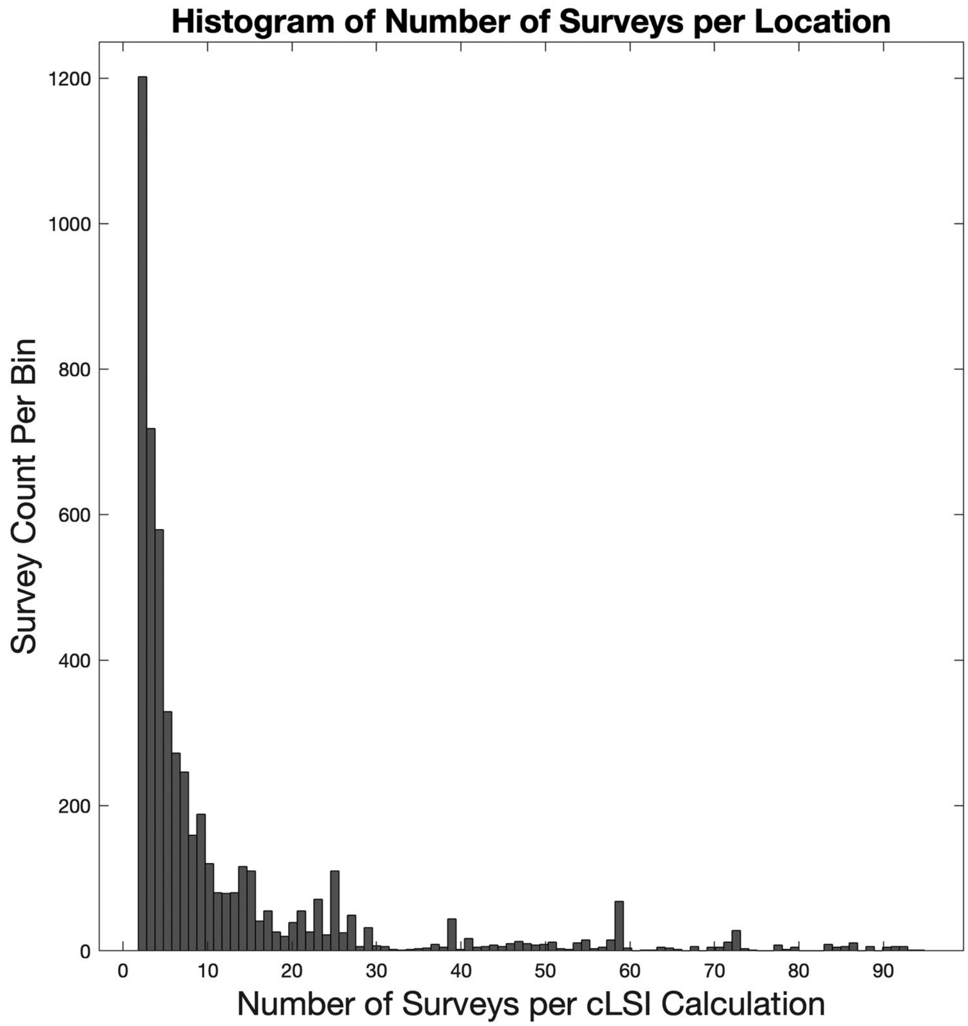

Figure 3. Histogram of the number of surveys included in each cLSI calculation.

Results

Least squared mean estimates and standard errors for the cLSI and cGSI for all listening environment characteristics are shown in Figure 4. Tables 2 and 3 provide the means for each characteristic and corresponding statistics for cLSI and cGSI, respectively (upper and lower bounds are 95% confidence intervals for the mean estimates). Higher cLSI indicates less variability of that listening environment characteristic in a given location, defined by the 10-m distance criterion for location. Higher cGSI indicates less variability of that listening environment characteristic overall, without respect to location. The degree of the location effect is represented by the mean differences between the cLSI and the cGSI. That is, the greater the difference between the mean cLSI and the mean cGSI for any given characteristic, the more location dependency that characteristic has.

It can be seen from Figure 4 that cLSI were higher than cGSI for all characteristics. Two-sample *t*-tests between cLSI and cGSI showed that cLSI were significantly higher than cGSI for all listening environment characteristics. Results of the two-sample *t*-tests along with mean differences between the cLSI and cGSI are shown in Table 4. These results suggest that there was a location dependency for all characteristics; that is, listening environment characteristics were the same more of the time when looking at a specific location than when looking at listening environments generally. If, for example, participants were always in quiet environments no matter where they completed surveys, the cLSI and cGSI for noisiness would be expected to be equal and close to one. If the noise level of listening environments varied widely in general and as well as in a given location, both the cLSI and cGSI would be expected to be equal and close to zero. The results presented here indicate that listening environment characteristics, in general, vary considerably, but vary significantly less when looking at a specific location.

Although the cLSI were significantly higher than the cGSI, the cLSI indicated that even in a given location there was still considerable variability in listening environment characteristics. Reverberation was the most stable characteristic, followed by signal type and noisiness, each of which had cLSI greater than 0.7. Although the cLSI were significantly higher than cGSI for these characteristics, the mean differences were smaller than for other characteristics, indicating that these characteristics were generally more stable overall regardless of location than other characteristics. Seventy percent of surveys were completed in the participants' homes, which likely contributed to the high stability of reverberation and noisiness. Particularly less stable characteristics were listening activity, noise location, talker familiarity, and visual cues. Mean differences between the cLSI and cGSI for these characteristics were also relatively large, indicating that these characteristics were perhaps more location-dependent than other characteristics. Pairwise comparisons with Tukey adjustments showed that cLSI differed significantly between nearly all

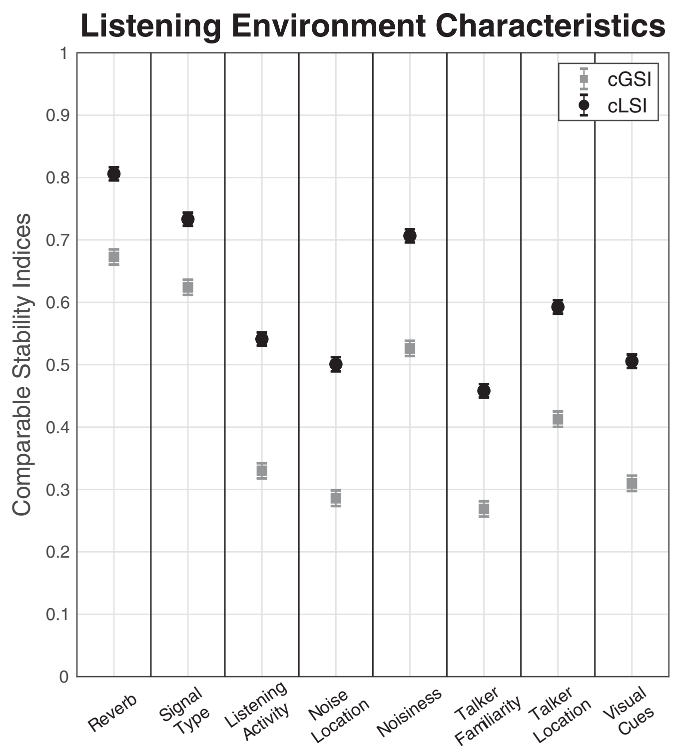

Figure 4. Mean cLSI and cGSI and standard errors for all listening environment characteristics.

Table 2. Least square means and corresponding statistics for cLSI.

Characteristic least squares means: cLSI						
Characteristic	Estimate	Standard error	t	p	Lower	Upper
Reverberation	0.81	0.01	76.77	<0.001	0.79	0.83
Signal type	0.73	0.01	69.83	<0.001	0.71	0.75
Listening activity	0.54	0.01	51.54	<0.001	0.52	0.56
Noise location	0.50	0.01	43.98	<0.001	0.48	0.52
Noisiness	0.71	0.01	67.30	<0.001	0.69	0.73
Talker familiarity	0.46	0.01	42.63	<0.001	0.44	0.48
Talker location	0.59	0.01	54.89	<0.001	0.57	0.61
Visual cues	0.51	0.01	47.03	<0.001	0.48	0.53

characteristics ($p < 0.01$). The only exception to this was noise location and visual cues ($t = -0.69$, $p = 0.99$). All cGSI differed significantly among characteristics ($p < 0.01$). Pairwise comparisons between all cGSI and cLSI for all characteristics are shown in Tables 5 and 6, respectively. These results suggest that how much listening environment characteristics changed over time was significantly different among nearly all characteristics when looking at a specific location and all characteristics when looking at listening environments generally.

Discussion

The primary purpose of the present study was to determine whether listening environment characteristics remained the same more often in a specific location than in listeners' environments overall. This study used GPS tagging to define specific locations as surveys taken within 10 m of each other. Then, stability indices were calculated based on the number of times listeners reported the same listening characteristics in that location. Stability indices for specific locations were compared to those for listening environments overall to determine whether there was a location dependency for listening environment characteristics.

Table 3. Least square means and corresponding statistics for cGSI.

Characteristics least squares means: cGSI						
Characteristic	Estimate	Standard error	t	p	Lower	Upper
Reverberation	0.67	0.01	55.22	<0.001	0.65	0.70
Signal type	0.62	0.01	51.22	<0.001	0.60	0.65
Listening activity	0.33	0.01	27.08	<0.001	0.31	0.35
Noise location	0.29	0.01	22.86	<0.001	0.26	0.31
Noisiness	0.53	0.01	43.18	<0.001	0.50	0.55
Talker familiarity	0.27	0.01	21.87	<0.001	0.24	0.29
Talker location	0.41	0.01	33.53	<0.001	0.39	0.44
Visual cues	0.31	0.01	25.21	<0.001	0.29	0.33

Table 4. Mean differences between cLSI and cGSI for all listening environment characteristics.

Differences between cGSI and cLSI				
Characteristic	Difference of means	Standard error	t	p
Reverberation	0.13	0.02	8.29	<0.001
Signal type	0.11	0.02	6.79	<0.002
Listening activity	0.21	0.02	13.13	<0.001
Noise location	0.21	0.02	12.70	<0.001
Noisiness	0.18	0.02	11.22	<0.001
Talker familiarity	0.19	0.02	11.60	<0.001
Talker location	0.18	0.02	11.00	<0.001
Visual cues	0.20	0.02	12.00	<0.001

cGSI and cLSI were significantly different for all characteristics.

Table 5. Pairwise comparisons between cGSI for all listening environment characteristics.

cGSI differences between characteristics					
Characteristic	Characteristic	Difference of means	Std. Err.	t	p
Reverb	Signal type	0.05	0.0033	14.59	<0.001
Reverb	Listening activity	0.34	0.0033	102.68	<0.001
Reverb	Noise location	0.39	0.0044	88.12	<0.001
Reverb	Noisiness	0.15	0.0033	43.92	<0.001
Reverb	Talker familiarity	0.40	0.0037	109.15	<0.001
Reverb	Talker location	0.26	0.0038	69.26	<0.001
Reverb	Visual cues	0.36	0.0037	98.07	<0.001
Signal type	Listening activity	0.29	0.0033	88.09	<0.001
Signal type	Noise location	0.34	0.0044	77.01	<0.001
Signal type	Noisiness	0.10	0.0033	29.33	<0.001
Signal type	Talker familiarity	0.36	0.0037	95.99	<0.001
Signal type	Talker location	0.21	0.0038	56.29	<0.001
Signal type	Visual cues	0.31	0.0037	84.91	<0.001
Listening activity	Noise location	0.04	0.0044	10.00	<0.001
Listening activity	Noisiness	−0.20	0.0033	−58.76	<0.001
Listening activity	Talker familiarity	0.06	0.0037	16.51	<0.001
Listening activity	Talker location	−0.08	0.0038	−22.02	<0.001
Listening activity	Visual cues	0.02	0.0037	5.43	<0.001
Noise location	Noisiness	−0.24	0.0044	−54.70	<0.001
Noise location	Talker familiarity	0.02	0.0047	3.69	0.007
Noise location	Talker location	−0.13	0.0047	−26.88	<0.001
Noise location	Visual cues	−0.02	0.0047	−5.10	<0.001
Noisiness	Talker familiarity	0.26	0.0037	69.53	<0.001
Noisiness	Talker location	0.11	0.0038	30.22	<0.001
Noisiness	Visual cues	0.22	0.0037	58.45	<0.001
Talker familiarity	Talker location	−0.14	0.0041	−35.36	<0.001
Talker familiarity	Visual cues	−0.04	0.0040	−10.21	<0.001
Talker location	Visual cues	0.10	0.0041	25.28	<0.001

cGSI were significantly different between all pairs of characteristics.

Recall that the purpose of this study was not to determine whether fluctuations in listening environment characteristics in one location over time affected hearing aid preferences or benefit. Furthermore, the purpose of this study was not to identify common listening environment characteristics (for descriptions of common listening environment characteristics for these

Table 6. Pairwise comparisons between cLSI for all listening environment characteristics.

cLSI differences between characteristics					
Characteristic	Characteristic	Difference of means	Std. Err.	t	p
Reverb	Signal type	0.07	0.00	15.24	<0.001
Reverb	Listening activity	0.26	0.00	55.40	<0.001
Reverb	Noise location	0.31	0.01	46.92	<0.001
Reverb	Noisiness	0.10	0.00	20.79	<0.001
Reverb	Talker familiarity	0.35	0.01	65.58	<0.001
Reverb	Talker location	0.21	0.01	39.53	<0.001
Reverb	Visual cues	0.30	0.01	56.66	<0.001
Signal type	Listening activity	0.19	0.00	40.16	<0.001
Signal type	Noise location	0.23	0.01	35.72	<0.001
Signal type	Noisiness	0.03	0.00	5.55	<0.001
Signal type	Talker familiarity	0.27	0.01	51.84	<0.001
Signal type	Talker location	0.14	0.01	26.03	<0.001
Signal type	Visual cues	0.23	0.01	42.92	<0.001
Listening activity	Noise location	0.04	0.01	6.20	<0.001
Listening activity	Noisiness	−0.17	0.00	−34.61	<0.001
Listening activity	Talker familiarity	0.08	0.01	15.63	<0.001
Listening activity	Talker location	−0.05	0.01	−9.54	<0.001
Listening activity	Visual cues	0.04	0.01	6.70	<0.001
Noise location	Noisiness	−0.21	0.01	−31.64	<0.001
Noise location	Talker familiarity	0.04	0.01	6.18	<0.001
Noise location	Talker location	−0.09	0.01	−13.19	<0.001
Noise location	Visual cues	0.00	0.01	−0.69	0.999
Noisiness	Talker familiarity	0.25	0.01	46.84	<0.001
Noisiness	Talker location	0.11	0.01	21.12	<0.001
Noisiness	Visual cues	0.20	0.01	37.92	<0.001
Talker familiarity	Talker location	−0.13	0.01	−23.00	<0.001
Talker familiarity	Visual cues	−0.05	0.01	−8.22	<0.001
Talker location	Visual cues	0.09	0.01	14.90	<0.001

cLSI were significantly different between all pairs of characteristics except for noise location and visual cues.

participants, see Wu et al. (2018)). Rather, the purpose of this study was to determine whether listening environment characteristics that might affect hearing aid preferences or benefit changed in one location over time, and therefore whether hearing aid settings chosen in one location might still be preferred or yield the same benefit in that location at a later time. This study found that there was a clear location dependency for listening environment characteristics. There was less change in all listening environment characteristics when a specific location was examined compared to listeners' environments overall.

The secondary purpose of this study was to compare listening environment characteristics in order to determine which listening environment characteristics were relatively more or less stable in one location over time than other characteristics. This study found that the degree to which listening environment characteristics changed over time both in a given location and in general differed significantly between nearly all characteristics. That is, some characteristics changed over time significantly less than other characteristics. Reverberation was the most stable characteristic. It should be noted here again that reverberation was not measured directly but was simply coded as high or low based on reported room size and presence or absence of carpet. To be sure, this is not a detailed or accurate way of measuring the actual amount of reverberation in a listening environment, which might be expected to fluctuate based on many other factors such as architectural features, building materials, and objects in the room. Further, the effect of reverberation on listening performance is a function not only of the amount or duration of reverberation, but also of the position of the listener within the room. That is, listeners closer to the source in a reverberant space likely have a better direct-to-reverberant ratio, and therefore likely better-listening performance, than a listener farther away from the source and with a poorer direct-to-reverberant ratio (Boothroyd 2004; Bradley, Sato, and Picard 2003). However, this way of coding reverberation has an advantage. Namely, because reverberation was coded based on room characteristics, and because the stability indices for reverberation were high, it may indicate that the GPS coordinates and 10-m "same location" criterion were accurate enough to be room-specific to a large degree. This is perhaps an encouraging finding if GPS is to be used for controlling hearing aid behaviour. Furthermore, although reverberation may change depending on, for example, the number of people in a given room, it also makes intuitive sense that the amount of reverberation for any given room would remain grossly stable over time. The mean difference between the cLSI and cGSI for reverberation was not, however, very large. This may suggest that the high degree of stability observed for reverberation was in part due to a homogeneity of room size and carpet presence in listeners' environments overall.

The signal type had a similarly high degree of stability over time. This suggests that whether listeners were listening to speech or non-speech signals depended on their location. This too makes a degree of intuitive sense; listeners may be likely to more often listen to speech in their living rooms, either in conversation or from a device such as a television or a phone, while they may be more likely to listen to environmental sounds when they are outdoors. Similarly to reverberation, however, the mean difference between the cLSI and cGSI for the signal type was relatively small. This may indicate that most of the active listening events were of one signal type or the other – likely speech (e.g. Wagener, Hansen, and Ludvigsen 2008; Wu et al. 2018). So although there is a location dependency for whether listeners are listening to speech or non-speech, the dependency is modest.

Noisiness was the third most stable listening environment characteristic. The relatively high cLSI for noisiness suggests that locations that are quiet are usually quiet while locations that are noisy are usually noisy. This is consistent with findings that show that commercial areas have higher overall sound levels than residential areas (King et al. 2012). That is, it is more likely to be quiet if a listener is at home and more likely to be noisy if they are in a commercial setting. The mean difference between the cLSI and the cGSI was larger for noisiness than reverberation and signal type, indicating a greater location dependency for noisiness. However, the cGSI was still ~0.5, indicating that noise levels fluctuated only moderately overall for these listeners (lower cGSI indicates greater overall fluctuation). A possible reason for this is that older adults spend a significant amount of time in relatively quiet environments (Humes et al. 2018; Klein et al. 2018; Wu and Bentler 2012; Wu et al. 2018).

Less stable characteristics were talker location, listening activity, visual cues, noise location, and talker familiarity, all of which showed cLSI between 0.45 and 0.6. What type of listening the listener was engaged in, the orientation of the signal and the noise, and access to visual cues varied more in a given location over time than reverberation, signal type, and noisiness. It is likely that in a given location a listener was sometimes talking on the phone, watching television or other media, or engaged in conversation. Where the talker and the noise were located in these situations and whether the listener could see the talker varied considerably as well. Still, these characteristics were also more stable in a given location than in general – and the location effect, based on the difference in means between the cLSI and cGSI for these characteristics, was larger than for reverberation and signal type. The reasons for this may be simple. For example, a listener is probably more likely to watch television in their living room than outside, at work, or at a restaurant, and is probably more likely to engage in group conversations in diffuse noise when outside their home than in their home.

Most of the surveys were completed in the participant's home with 10 or fewer people in the room. It may be argued that this could bias the results in favour of greater stability, as a listener may have more control over the environment in their home than outside their own, resulting in greater stability for many characteristics that might have been observed if only environments outside the home were considered. It is not possible with the results of this study to specifically address the listening environment characteristic stability as a function of environment type. It is important to note, however, that many surveys at home were likely completed while watching television. It is not then clear that many characteristics, such as visual cues, talker familiarity, and noisiness, would necessarily be more stable at home than elsewhere. However, interpreting these data with respect to TV watching is complicated. For example, it is not clear whether a participant reported on the level of noisiness in the TV program or in the background, or visual cues from the TV or from a family member or partner in the room watching with them. An argument could also be made that talker familiarity and visual cues may be more stable outside the home, as it might be that listeners are more likely to be facing a person they know when in a restaurant, for example, than when browsing television shows. Further, listening environment characteristics might not be expected to be similarly stable in different rooms of a listener's home. The high stability index for reverberation seems to support this. Therefore, GPS, if accurate enough, could presumably be used to set preferences for different rooms in a listener's home. However, more research is needed to clarify the stability of home listening environments and how listening activities within the home, such as TV watching, might affect the effectiveness of GPS-tagged hearing aid settings within the home. The purpose of this study was to directly investigate the ability of GPS to predict listening environment characteristics, and therefore no attempt was made to complete separate analyses based on whether the listener was at home or not. This remains an important area for future research.

Listening environment characteristics fluctuate, but whether this fluctuation is due to differences between tokens of the same listening environment class (e.g. different kitchens, different restaurants, etc.) or differences within a single token over time (e.g. the same kitchen or restaurant at different time points) is somewhat ambiguous in prior research (Smeds, Wolters, and Rung 2015; Wagener, Hansen, and Ludvigsen 2008; Wu et al. 2018). The findings from this study seem to support the idea that at least some of the variability of within-class listening environments is likely due to the fluctuating nature of a listening environment over time in a given place. That is, some of the variability in sound pressure levels and signal-to-noise ratios within classes noted in the literature may be due in part to changes in characteristics in a location over time, as opposed to being wholly due to between-token differences within the class. For example, it is likely that the wide variability reported in sound pressure levels in kitchens is due to different levels of sound in any given kitchen over time, rather than being wholly due to variations between different kitchens. An implication of this is that classifying listening environments based on environment type (kitchen, home, etc.) may not be the only or best approach to understanding listening environments. Our results seem to support the approaches taken by Wolters et al. (2016) or Wu et al. (2018), where listening environments were classified either by intention and task (Common Sound Scenarios) or by noise, visual cues, noise location, and talker location (Prototype Listening Situations), respectively.

Implications

The results of this study suggest possible implications for the use of GPS in hearing aids. GPS-enabled hearing aids, which can revert to settings previously set by a user in a specific location, operate on the assumption that listening environment characteristics that might affect hearing aid preferences or benefit remain the same in a given location. The results of this study offer mixed support for this. Listening environment characteristics were indeed more stable over time in a single location than in the overall listening environments of participants. However, for most characteristics, there was still a large degree of fluctuation. That is, for GPS-tagged preferences to be consistently effective, characteristics that might affect hearing aid preferences or benefit would need to have stability indices close to one. The highest indices observed in this study were 0.81 (reverberation), 0.73 (signal type), and 0.71 (noisiness). From these results, hearing aid settings chosen based on, for example, how noisy the environment was would only be expected to be appropriate approximately three-quarters of the time.

Other characteristics including talker and noise location, visual cues, and listening activity, all of which have been shown to affect hearing aid preferences, were less stable, indicating that hearing aid preferences chosen based on these characteristics may only be appropriate in that location about half of the time. For example, fixed directional microphones may not show consistent benefits in a given location over time. This might indicate a need for effective automatic adaptive directional microphones regardless of location. Although visual cues and talker familiarity would not be expected to affect hearing aid processing directly, they would be expected to affect listening performance and hearing aid satisfaction, and thus might limit benefits of GPS-tagged hearing aid preferences. For example, a GPS-tagged hearing aid may be function well in an environment that always has the same level of noisiness. However, if visual cues and talker familiarity varied considerably in that location, we might expect listening performance as well as hearing aid satisfaction to vary in that location. This may make it seem as though GPS-tagging is ineffective, though the GPS-tagging is simply limited by the fluctuation of other characteristics that affect listening performance and hearing aid satisfaction.

The benefit of GPS-tagged hearing aid settings might then be predicted to be mixed. It is worth noting here that the stability indices in this study were based on a 10-m criterion. Presumably, as this criterion gets larger, and therefore the location increasingly less specific, the stability indices decrease. Therefore, for the GPS-enabled hearing aid feature to be effective, it would likely need to be quite accurate and use a relatively constrained criterion for the same location designations. Even the 10-m criterion may be too generous in many situations to define two places as the same location. It is easy to imagine, for example, a busy coffee shop next door to a quiet bookstore. These two places would likely have quite different listening environments, and yet by the criterion used in this study could be considered the same location. Even using this relatively broad operating definition of location, 29.26% of surveys were excluded from the analysis because they were completed in unique locations—places where the participant completed only one survey within a 10-m radius. Hearing aid users may not find it useful to spend time geo-tagging hearing aid preferences for locations they may rarely or not ever return to. The number of unique locations could be reduced by using a more generous location criterion, but there is likely a trade-off between making a location criterion large enough that tagged locations are not largely unique while at the same time making the location criterion small enough that the criterion means the same location. Ultimately, using GPS in both hearing aid technology and hearing aid research presents interesting opportunities but many practical and methodological challenges as well.

Limitations

This study had several limitations, and interpretations of these data should be tempered by several considerations. All data presented here was based on self-report. Surveys asked participants to report on the characteristics present for most of the time in the prior 5 min of their active listening situation. Little is known about how listeners remember and make judgments about their listening environments, even within relatively short time windows. It is likely that characteristics may fluctuate considerably in one location even within a 5-min time window. For example, the talker may move around the listener, changing both the talker location and access to visual cues. Or, if the listener is attending to more than one talker, the talkers may differ in their familiarity to the listener. How listeners report on such situations is unknown, and may affect the test–retest reliability of the EMA. In the above example, a listener who is attending to talkers of different familiarity could report they are familiar with the talker on one EMA and only somewhat familiar on a different EMA, even though the listening situation is the same. Low test–retest reliability on the EMA would result in lower stability indices. These lower indices, however, would not be a reflection of the listening environment per se but rather of how listeners may report on similar environments differently at different times. A study of the test–retest reliability of EMA would clarify the interpretation of the stability indices reported here. Further, repeated measures of self-report may be influenced by a number of individual factors that were not accounted for in this study, such as differences in working memory or other cognitive abilities. Finally, because listening environment characteristics may be dynamic within one listening event, the EMA utilised in this study might have been improved by explicitly asking participants to report on how much listening environment characteristics changed within the listening event, such as asking them to report the perceived percentage of time the signal of interest was in various locations during the 5-min window, or the degree to which the signal of interest was spatially dynamic.

This study examined only active listening situations. Hearing aid users likely wear their hearing aids, however, in many situations in which they are not actively listening, and they may have specific preferences and perceived benefits for non-active listening situations that differ from active listening situations. For example, many hearing aids include a program that may make noisy situations in which the user is not actively listening more comfortable. This study did not systematically examine these listening situations or the degree to which listening environment characteristics may change over time differently in passive and active listening situations. This remains an important area for future research.

The population of participants in this study may not have had listening environments that represented the types of listening environments experienced by the population generally. Specifically, the findings observed in this study might differ from a similar study examining younger listeners. Older listeners may be less active than younger listeners and may spend more time in relatively quiet environments than younger listeners (Wu and Bentler 2012; Wu et al. 2018). This may result in higher stability indices than would be observed in participants with more diverse listening environments. Further, due perhaps in part to the demographics of the population, most of the surveys were taken in the participants' homes, likely often while participants were watching television. Although it was important for this study to include these data as television watching represents an important listening situation for many listeners (Klein et al. 2018), it is not clear how this might affect listening environment characteristic stability. Further, as these were research participants, they might have been motivated to encounter a wider variety of listening environments than the hearing aid user population at-large. Although prior work on this group of participants indicates that they do not in fact encounter a very large variety of listening environments, how their auditory lifestyle compares to the population at-large is unknown (Klein et al. 2018). It might also be a concern that participants might have altered their behaviour or lifestyle due to wearing hearing aids for the first time or using new hearing aid processing features, drawing into question how representative these data might be. However, there is no indication based on prior analyses of these participants that hearing aid use altered their behaviour or lifestyle (Klein et al. 2018).

Finally, the calculations necessary to examine the stability of listening characteristics and to compare them to one another in this study were complex. The data used for this study was collected as part of a larger study, the primary purpose of which was not to examine the stability of listening environment characteristics over time. Therefore, this study served simply as a preliminary examination of the dynamic nature of listening environments. Experiments designed explicitly for this purpose could be better designed to directly and more simply address the complex nature of listening environment fluctuations over time and place.

Conclusion

In this study, we have made a preliminary investigation into how much listening environment characteristics change in a location over time. To estimate the degree of change over time, geo-tagged EMAs were used to generate comparable stability indices for listening environment characteristics. The results indicate that listening environment characteristics change less over time when looking at a specific location, rather than across all the environments of listeners. This suggests there is a location-dependency of listening environment characteristics. However, there was still considerable fluctuation among most listening environment characteristics even in a specific location. The results of this study offer mixed support for the use of GPS in configuring hearing aid settings as well as highlight the need to more research on the dynamic nature of listening environments in the real world.

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