Evaluating a Hearing Loop Implementation for Live Orchestral Music

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Structured Abstract (up to 500 words)

Introduction: Live music creates a sense of connectedness in older adults, which can help alleviate the social isolation frequently associated with hearing loss and aging. However, most hearing aid (HA) users are dissatisfied with the sound quality for live music and rate sound quality as important to them. Assistive listening systems are frequently independent of a user's HAs and fall short in tailoring to each individual's hearing loss. The present study thus tested whether the use of a hearing loop would improve sound quality during an orchestral concert. **Method:** Participants with symmetrical moderate-to-severe hearing loss were assigned to use Sonova-provided HAs with a telecoil (n = 20) or their own HAs (n = 8) without a telecoil during a performance by the Hamilton Philharmonic Orchestra. We changed loop input to use microphones from the stage, balcony, or no feed every 5 minutes and collected associated sound quality and naturalness ratings. **Results:** Sound quality and naturalness ratings were highly related (r_{RM} = .81), though each provided unique insight. Repeated Measures ANOVA found significant differences among the loop feed conditions for sound quality and naturalness, with the No Feed condition significantly outperforming the House condition on sound quality ($t(18)$ = -3.73, adj-p = .005) and naturalness ($t(18)$ = -4.15, adj-p = .002). Mixed effects models allowed us to retain the richness of a repeated observation dataset and provided point estimates of the overall quality and naturalness among conditions; however, assumption violations of normality and homoskedasticity prevent further interpretation. **Conclusions:** Though hearing aid-integrated assistive listening systems are a promising option for improving live music for people with hearing loss, a hearing loop does not seem to be crucial for orchestral music. Future directions include improving lyric understanding for music with vocals and customizing user experience via Bluetooth Low Energy Audio systems.

Introduction

The role of hearing loss in social isolation is most frequently understood through the lens of difficulties understanding speech, particularly in noise. Often neglected in social isolation and hearing loss research is the role of live music in creating a sense of connectedness, healthy aging, and wellbeing (Hays et al., 2002; Hays & Minichiello, 2005). Though social isolation can affect all individuals with hearing loss (Bott & Saunders, 2021), there is particular concern in older adults due to not only the high incidence of hearing loss (65% of 70–79-year-olds; Feder et al., 2015), but also due to the growing concern over the relationship among hearing loss, social isolation, and dementia (Livingston et al., 2020; Shukla et al., 2020). Additionally, music's role in social bonding makes it an attractive target for allaying feelings of social isolation (Savage et al., 2021).

As hearing aids (HAs) have long been optimized for speech processing, most HA users report reduced enjoyment of live music (Greasley et al., 2020). Both hearing loss and HA signal processing present challenges for music listeners. Individuals with hearing loss have deficits in pitch and timbre discrimination, as well as atypical reverberation preferences for speech and music (Kirchberger & Russo, 2015; Reinhart & Souza, 2018). The causes of these deficits relate to impaired frequency selectivity, loudness recruitment, and audibility thresholds, only the lattermost of which can be addressed by amplification (Moore, 2016). In addition, HAs distort the music signal due to the its large dynamic and frequency ranges, and large crest factor, as well as through frequency lowering algorithms (Chasin, 2022). Experiencing distortion and feedback are relatively common issues, with feedback and distortion experienced by 50% and 33% of HA users, respectively (Madsen & Moore, 2014). Not only are HA users sensitive to distortion, they also report that sound quality for music is very or extremely important to them (Wigan et al., 2017). Nonetheless, opinions from HA users are mixed with respect to whether using HAs make music more enjoyable (Leek et al., 2008), with 41% of listeners reporting an increase in enjoyment, 37% reporting no improvement, while 19% report not using their hearing aids for music at all.

Assistive listening systems (ALS), such as a direct feed from the venue's mixing board to headphones worn by an audience member, bypass the aforementioned signal processing difficulties of HAs, but do not appropriately compensate for each individual's audiometric loss, nor can they solve the problems generated by the hearing loss itself. ALSs that connect to users' HAs are thus an attractive option for providing direct sound tailored to each individual. However, at present in most countries, there are no universal ALSs, though some countries, such as the UK and others in Northern Europe have widespread adoption of hearing loops and telecoil receivers are present in a large majority of HAs, in comparison to North America (Blaha, 2004). Though hearing loops have been around since the 1930's (Poliakoff & Sneath, 1939), and are used widely for speech applications, to our knowledge, there is no extant research detailing the use of a hearing loop or any ALS for live music.

In 2019, we ran a pilot study that led us to pursue using a hearing loop for live music rather than proprietary Bluetooth devices, as the Bluetooth-based system experienced more connectivity issues. Anecdotal feedback from a few expert musicians indicated that the loop sounded like a high-quality mono recording, but that this was not natural in the space of a reverberant concert hall. In the present study, we aimed to test whether a hearing-aid integrated ALS improved the sound quality of live orchestral music without negatively impacting how natural the music sounded in the large and reverberant FirstOntario Concert Hall.

Method

Participants.

Participants (*n* = 20, *n* = 10 females, median age = 71-years-old) with symmetric moderate-to-severe hearing loss were recruited from the Greater Hamilton and Toronto areas. They were asked to provide a recent audiogram (within 12 months); in lieu of a recent test, air conduction thresholds were collected in our lab. To be eligible, individuals needed to have a pure tone average (PTA; 500Hz, 1 kHz, 2 kHz, 4 kHz) ≥30 dB HL and ≤80 dB HL in at least one ear, in line with the fitting range of the study HAs. Only two participants had a PTA < 40dB HL in a given ear. With respect to symmetry, we excluded participants with more than 25 dB difference between the ears at any frequency. All participants were fitted with Unitron Discover Next behind-the-ear (BTE) HAs with telecoils that used replaceable batteries (DX Stride M 9) 2-3 weeks in advance of the concert by audiologists from Sonova Canada. Though prior hearing aid experience was not required, only one participant had not worn HAs before, whereas the rest had worn theirs for several years. Participants primarily used the automatic program for daily use. A boxplot of their audiograms is presented in Figure 1.

The BTE HAs were coupled to the ear with slim tubes and power domes, minimizing low frequency leakage wherever possible; alternate closed dome choices were provided (*n* = 6) if power domes were not acceptable to the participant. The HAs were programmed and verified with NAL-NL2; the prescription was changed to DSL Adult 5.0 or the settings adjusted if required. The VeriFit2 real ear measurement system was used for verification with the relevant prescriptive approach targets. Three participants made return visits for programming adjustments.

In addition, we recruited a group of participants who would use their own hearing aids. This group either was just outside of our inclusion criteria with respect to symmetry (*n* = 4), registered for the study with fewer than two weeks before the concert (*n* = 2), dropped out of the telecoil group due to ongoing work with their audiologist (*n* = 1), or were under the age of 18 (*n* = 1). Though these participants can serve as a useful baseline, the small sample makes inferential statistical analyses a challenge. Their audiograms are presented in Figure 2. All participants received free tickets to the concert as compensation for their time. This study was reviewed and approved by the McMaster Research Ethics Board (MREB #1975).

Procedure.

A temporary induction loop coil was installed in the upper balcony of FirstOntario Concert Hall, a 2,200-seat venue. The distance from the back of the balcony to the front of the stage was 27 m and to the back of the stage was 37 m. The loop enclosed 6 rows, each 17m wide.

One week in advance of the concert, participants were brought in to familiarize themselves both with the telecoil program and its functionality, as well as with the concert procedure, and how to respond using the response tablets. For the concert, participants arrived at 18:30 on May 13, 2023, an hour before the concert began at 19:30. Participants with telecoil hearing aids had their programs switched to the telecoil program only with 0dB attenuation for the HA mic, and had their batteries replaced. Once seated with their family members inside the hearing loop, we calibrated the loudness levels to ensure that the loop was not uncomfortably loud for any of the participants, though one participant would report difficulties before intermission.

Experimental Conditions and Responses.

We created 2 mixes to send to the telecoil, one from microphones on the stage and one from microphones in the house on the first balcony face, the latter of which are the hall's default feed for their infrared-based assistive listening system. Stage microphones were placed in front of each section: Violin I, Violin II, Viola, Cello, and Bass each used a Sennheiser MKH-8040;

Flute, Oboe, Clarinets, and Bassoons each used a Shure Beta 181; Horns, Trumpets, and Trombones each used a Sennheiser MD 431, and the Timpani used a Sennheiser MK4. This feed was mixed by the concert hall's chief audio engineer using their usual digital audio mixing board. Balcony microphones were AudioTechnica AT2020s, and these were again mixed by the concert hall's chief audio engineer. To account for the distance from the stage to the loop, we included a delay for these feeds so that they would match the timing of the direct sound. We adjusted loop levels using a KEMAR mannequin programmed with HAs with unity gain set to the telecoil program, listening over equalized headphones. KEMAR microphones were recorded throughout the concert.

During the concert, we switched among the stage, house, and no loop input feeds every 5 minutes and asked participants to rate the sound quality and naturalness on a slider scale from 1-5 (worst to best and least to most natural, respectively) using an Android tablet app. The telecoil program was still used for the No Feed condition, but no telecoil input was given. The experiment timing was synchronized with global time, such that on 5-minute intervals (19:30, 19:35, 19:40, etc.), participants would rate the previous 5 minutes. The times each condition was implemented was randomized ahead of the concert.

There were four pieces of music, two before and two after intermission. Before and after intermission, there was one short modern piece (~5 minutes) and one long classical piece (23-32 minutes). For the purposes of our analysis, we will focus on the long classical pieces (Mozart Violin Concerto No. 4 and Beethoven Symphony No. 5), as they had multiple experimental conditions, and were more familiar to the participants.

Data Cleaning and Summary.

The app prompted participants to make sound quality and naturalness ratings using sliders on the same screen. Here we refer to a “response” as this paired observation, whereas a “rating” refers to the numeric sound quality or naturalness rating. The app was programmed to prompt every five minutes, and only allowed one response per 5-minute interval. Nine of the tablets periodically malfunctioned and prompted the participant for a response multiple times in a 5-minute interval, occurring for 13 out of the 424 responses we collected; the first response for a given 5-minute interval was retained and later responses were excluded. Next, we excluded 18 responses that occurred more than a minute after the app prompt and condition change. Additionally, another participant took her hearing aids out because they were too loud before intermission; we thus excluded 7 responses for this participant from before intermission from all analyses. In sum, we collected 424 responses during the classical pieces from both groups. We removed 13 responses from the data for being recorded from an erroneous prompt, 18 responses for being recorded more than 59 seconds after the prompt to respond, and 6 from one participant’s data before intermission, leaving 387 responses, 270 of which were from the telecoil group, and 117 from the own device group. One additional participant had only 5 valid responses and none in the Stage condition; this participant was removed from repeated measures ANOVA analyses. Each participant had to have at least three responses per condition to be included, with the exception of the participant whose pre-intermission data was excluded, who had only 2 in the Stage condition. On average, each participant in the telecoil group had 5.50 responses recorded for the No Feed condition, 4.35 responses for the House condition, and 3.84 responses for the Stage condition. The distributions of these quality and naturalness scores over the course of the concert are presented in Figures 3 and 4, respectively. Each individual’s quality and naturalness ratings throughout the concert are presented in Supplemental Materials.

Results

Repeated Measures Correlations Between Sound Quality and Naturalness.

First, we tested the strength of the linear relationship between sound quality and naturalness ratings. Because we could not assume independence, we ran repeated-measures correlations on the telecoil group's sound quality and naturalness ratings for each time period from the classical pieces shown in Figures 3 and 4. The repeated measures correlation was extremely high ($r(251) = .79$, $p < .001$), as was to be expected.

Sound Quality and Naturalness Across House, Stage, and No Feed Conditions.

As each condition had multiple responses, we averaged each participant's responses for each of the three conditions. The reported standard deviation is that of the per participant mean ratings, which is given in Table 1.

To test whether there were differences in sound quality and naturalness among the experimental conditions, we conducted two repeated measures ANOVAs. All three conditions met assumptions for normality under the Shapiro-Wilk test and had equal variances under Levene's test. There were significant differences in sound quality ($F(2,36) = 5.427$, $p = .01$) and naturalness ($F(1.4,25.6) = 5.042$, $p = .02$). Bonferroni-corrected post-hoc tests revealed that the No Feed condition significantly outperformed the House feed for sound quality ($t(18) = -3.73$, adj-$p = .005$) and naturalness ($t(18) = -4.15$, adj-$p = .002$). No other comparison reached significance after Bonferroni-correction, though the No Feed condition was significantly higher than the Stage feed before correction ($t(18) = 2.24$, adj-$p = .11$). Means and standard errors are presented in Figure 5.

To retain the richness of repeated observations per condition in our data, we ran linear mixed effects models, including each participant with their own random intercept. This also allowed us to retain the participant who did not have any valid responses for the Stage condition. For each of sound quality and naturalness, we ran a null model, only including the random intercept per participant and compared it to a model with condition (i.e., microphone mix) as a fixed effect in addition to the random intercept. ICCs were calculated using the null model for quality (ICC = .41) and naturalness ratings (ICC= .38). This indicates that 41% and 38% of the variance in quality and naturalness scores, respectively, is between subjects, which is ideal midpoint for mixed-effects models. The distributions of both quality and naturalness were highly left-skewed (-.91 and -.77, respectively), with 25% and 26% of all responses for quality and naturalness falling above 4.8 out of 5, revealing a clear ceiling effect. Full model results are presented in Table 2.

For sound quality, the intercept (House condition) was 3.75 (95% CI = [3.45 4.05]); the additional effect of the No Feed condition was 0.28 and the Stage condition had an additional effect of 0.22. The standard deviation of the random intercepts was estimated at 0.60, which is considerable between-subject variation in this context. When comparing to the null model, the full model was a significantly better fit ($\chi^2(2) = 7.45$, p = .02), which agreed with AIC, log-likelihood, and deviance all improving. Interestingly, BIC increased from 663.76 to 667.53, likely due to the increased numbers of fit parameters. Additionally, upon examining the QQ plot and plotting the fitted values against the residuals, a clear picture of heteroskedasticity emerged. Additionally, the residuals were not normally distributed, failing the Shapiro-Wilk test of normality ($W = .96$, $p < .001$). Neither log-transforming nor rationalized arcsine transforming (Studebaker, 1985) the data was not effective in alleviating these assumption violations due to the number of responses at 5.00. For these reasons, the reported *p*-value suggesting improved model fit is not interpretable.

For naturalness, the intercept (House condition) was 3.72; the additional effect of the No Feed condition was .26 and the Stage condition had an additional effect of -.01. The standard deviation of the intercepts was estimated at 0.58, which is highly similar to the sound quality model. When comparing to the null model, we again obtain highly similar results to the quality model; the full model was significantly better fit ($\chi^2(2) = 7.90$, $p = .02$), which agreed with AIC, log-likelihood and deviance all improving. Again, BIC increased from 679.95 to 683.26, again likely owing to the number of increased parameters. As was the case for the quality ratings, examining the QQ plot and plotting the fitted values against the residuals demonstrated a clear picture of heteroskedasticity. Additionally, the residuals were not normally distributed, failing the Shapiro-Wilk test of normality ($W = .98$, $p < .001$). Neither log-transforming nor rationalized arcsine transforming the data was not effective in alleviating these assumption violations due to the number of responses at 5.00. For these reasons, the reported *p*-value suggesting improved model fit is not interpretable.

Discussion

Our study examined the effect of using hearing-aid integrated assistive listening technology on listeners' perception of sound quality and naturalness during a live concert. Specifically, we installed an induction loop and had users with telecoil hearing aids periodically rate the quality and naturalness of three different feeds during a performance of Beethoven Symphony No. 5 and Mozart Violin Concerto No. 4, one a mix of microphone inputs from the stage (Stage condition), one the concert hall standard feed from microphones on the first balcony face (House), and one no input (No Feed). Using RMANOVA, we found significantly reduced quality and naturalness ratings when using House feed. The additional information provided by the mixed effect models gave us point estimates for each feed condition, as well as an estimate of the between-subject intercept variance across all conditions, revealing considerable variability (SD = 0.60). Further, both models failed to meet multiple assumptions regarding the distribution of the residuals, due to strong ceiling effects. Nonetheless, the Stage condition point estimate was nearly identical to the House condition for naturalness, which may indicate that assistive feeds from the loop lead to a decrease in naturalness.

There are a few possible explanations for why the House condition resulted in lower ratings than the No Feed condition for sound quality and naturalness. One possible explanation is that the first balcony feed had higher levels of reverberation, picking up the hall's reverberation. In speech contexts, listeners with hearing loss tend to prefer lower reverberation, though the literature on music is less clear in this regard (Reinhart et al., 2016; Reinhart & Souza, 2018). Another possible explanation is that setting the delay through the mixing board based on the distance from the stage to the loop failed to account for the distance from the stage to the balcony mics, which was likely around 40 ms. In addition to these balcony-mic-specific issues, using a mono audio feed likely decreases naturalness. Though the naturalness differences between Stage and No feed conditions did not survive multiple comparison corrections, it is worth mentioning here as a possible factor explaining these differences. Nonetheless, when listening to the KEMAR recordings, which had HAs programmed at unity gain, obvious differences were not apparent across any of these dimensions, and discriminating among the conditions was challenging for a normal hearing listener.

This is the first published study of its type to assess implementation of an assistive listening system during a live concert. Due to the fact that the No Feed condition did not differ from the Stage condition, and outperformed the House condition, we conclude that loop-coil systems are not sufficient to improve the listening experience for orchestral music, possibly because they are monaural. This is not to say that other benefits from hearing-aid integrated technology were not present; regarding language, participants remarked on how inaccessible talks before each piece were without an assistive listening feed. There also may have been moments within the 5-minute rating intervals in which the feeds were more differentiated, but we were not able to capture this on a 5-minute time scale. Importantly, anecdotal responses from our participants indicated sincere gratitude that people were working to make concerts more accessible for individuals with hearing loss.

Future Directions.

We plan to turn our attention to vocal music until the release of Bluetooth Low Energy (LE) Audio technology is widely available. This shift is largely motivated by anecdotal responses from participants regarding audibility of speech during this concert and their expressed desire for better assistive systems in theatres. We thus plan to evaluate whether assistive listening systems for vocal music can improve lyric understanding, which can be a challenge even for people without hearing loss. Recent research showed listeners with hearing loss prefer mixes with higher vocal energy (Benjamin & Siedenburg, 2023), and it would be interesting to confirm whether this also applies in a naturalistic live concert situation.

Regarding the shifting landscape toward Bluetooth-based connectivity, we have used a handful of Bluetooth-based devices in other pilot studies, including those designed to connect users with their TVs. However, at present, these devices are proprietary and only work for their respective brands of hearing aids and have occasional connection issues that hearing loops do not. We have also examined the use of a proprietary Wi-Fi-based device that would send a feed to users' phones, but the latency from the device to the phone to the hearing aid was ~350 ms, with the majority of that delay being from the phone to the hearing aid. Bluetooth LE Audio aims to drastically reduce this latency to the point that it would be acceptable with respect to the simultaneity of the acoustic and assistive feeds while retaining the advantages of stereo sound and user customization.

Finally, from a user experience perspective, the end goal is for the user to have customizability over their mix, seamlessly integrated with highly flexible and intelligent automatic programs. An interface that would allow a user to balance the levels from their HA mic to acoustic input as well as a graphic equalizer provides unprecedented control over the sound reaching the hearing aid user's ears. More advanced setups could entail applications that give channel- or bus-specific sliders, allowing users to boost individual instruments or sections that are frequently inaudible to hearing aid users.

Summary and Conclusion.

In sum, we have provided the first published assessment of assistive listening systems for hearing aid users for live music. The results of this study indicate that current hearing-aid-integrated assistive listening systems are insufficient to provide widespread benefit for live music listening as long as the music is audible using the HA's internal microphones, which it often is during Western classical orchestral concerts. However, other benefits, such as increased accessibility to any spoken components of a concert and dedicated professionals working to improve their experience facilitate a more holistic view of concert accessibility. Future research will be aimed at creating best practice recommendations for different genres, as well as examining the impact that accessible systems for music have on community participation.

Table 1

Descriptive Statistics for Experimental Conditions, Averaged Data

Group	Telecoil		Own Device	
	Mean (SD)	*n*	Mean (SD)	*n*
Quality				
House	3.79 (.75)	19	4.01 (.86)	8
No Feed	4.06 (.64)	19	4.17 (.92)	8
Stage	3.98 (.63)	19	4.23 (77)	8
Naturalness				
House	3.73 (.68)	19	3.95 (.94)	8
No Feed	3.99 (.64)	19	4.18 (.79)	8
Stage	3.71 (.71)	19	4.21 (.77)	8

Note. Own Device group did not experience changes in condition. The scores are presented to show baseline variation across pseudo-conditions.

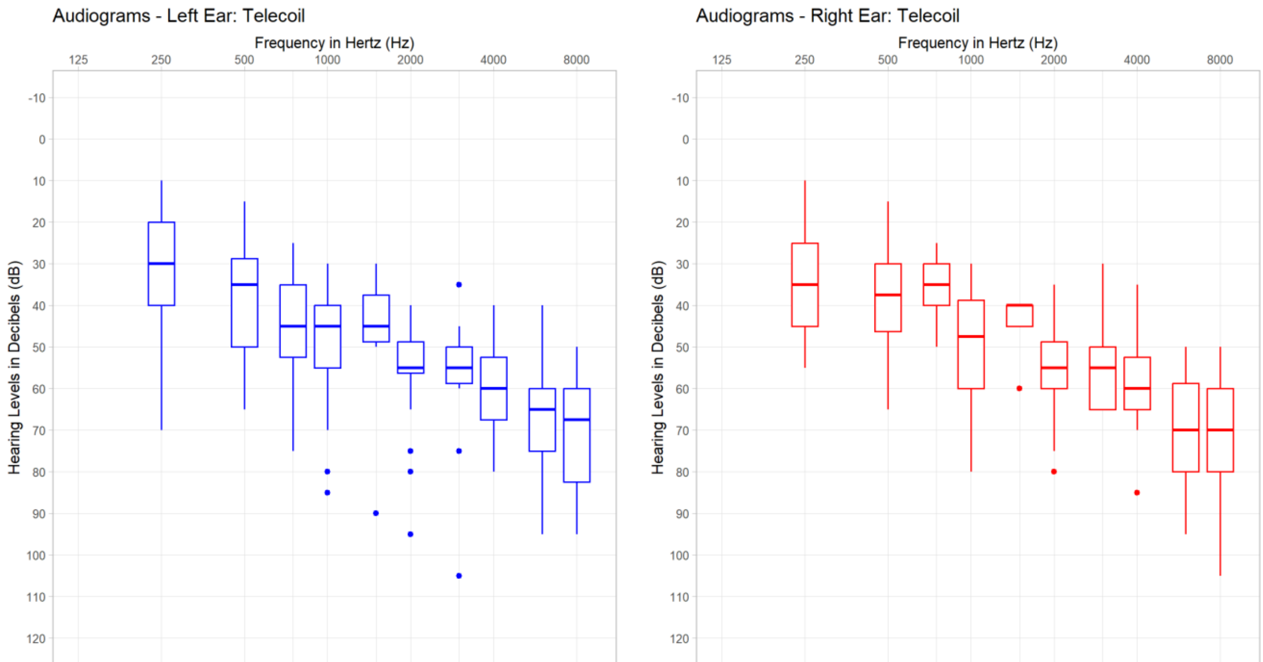
Table 2

Fixed Effects from Full Models for Quality and Naturalness

	Estimate	t-value	95% CI
Quality			
Intercept	3.75	24.26	[3.45 4.05]
No Feed	0.28	2.66	[0.07 0.47]
Stage	0.22	1.91	[-0.01 0.45]
Naturalness			
Intercept	3.72	24.35	[3.42 4.02]
No Feed	0.26	2.41	[0.05 0.47]
Stage	-0.01	-0.06	[-0.24 0.23]

Figure 1.

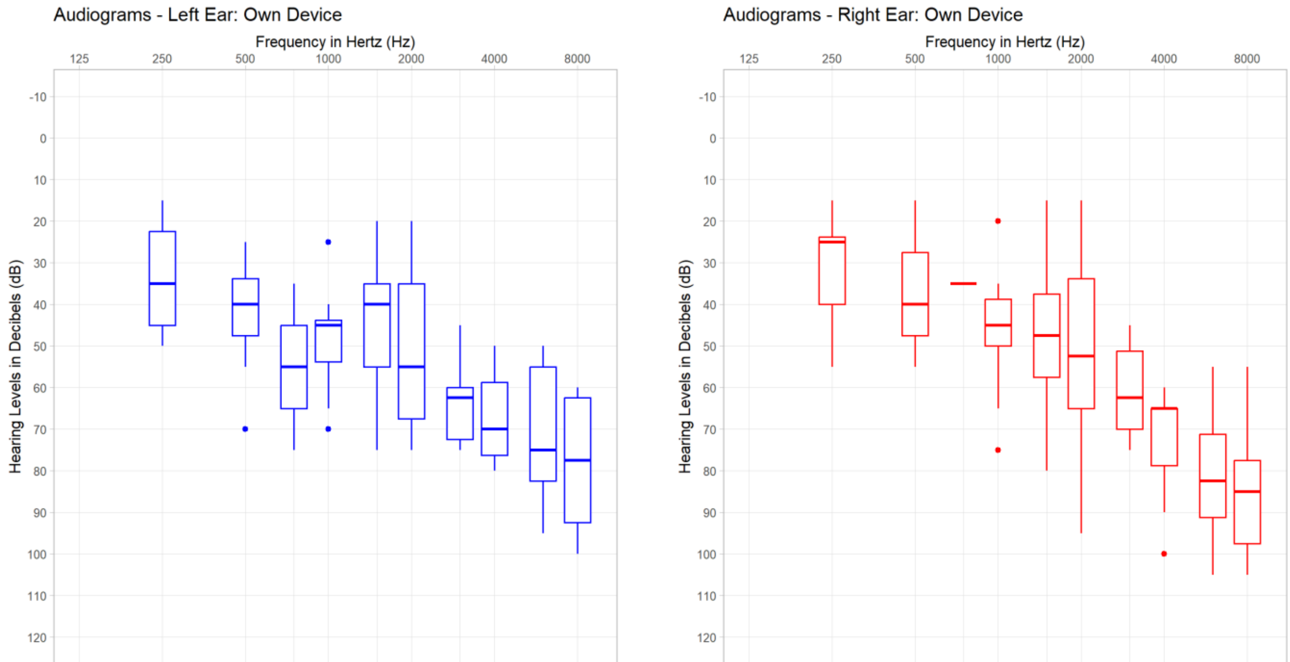
Boxplot of Audiograms from the Telecoil Group



Note. Outlier points lie outside of 1.5 times the interquartile range.

Figure 2.

Boxplot of Audiograms from the Own Device Group



Note. Outlier points lie outside of 1.5 times the interquartile range.

Figure 3.

Sound Quality ratings for the Telecoil and Own Device Groups

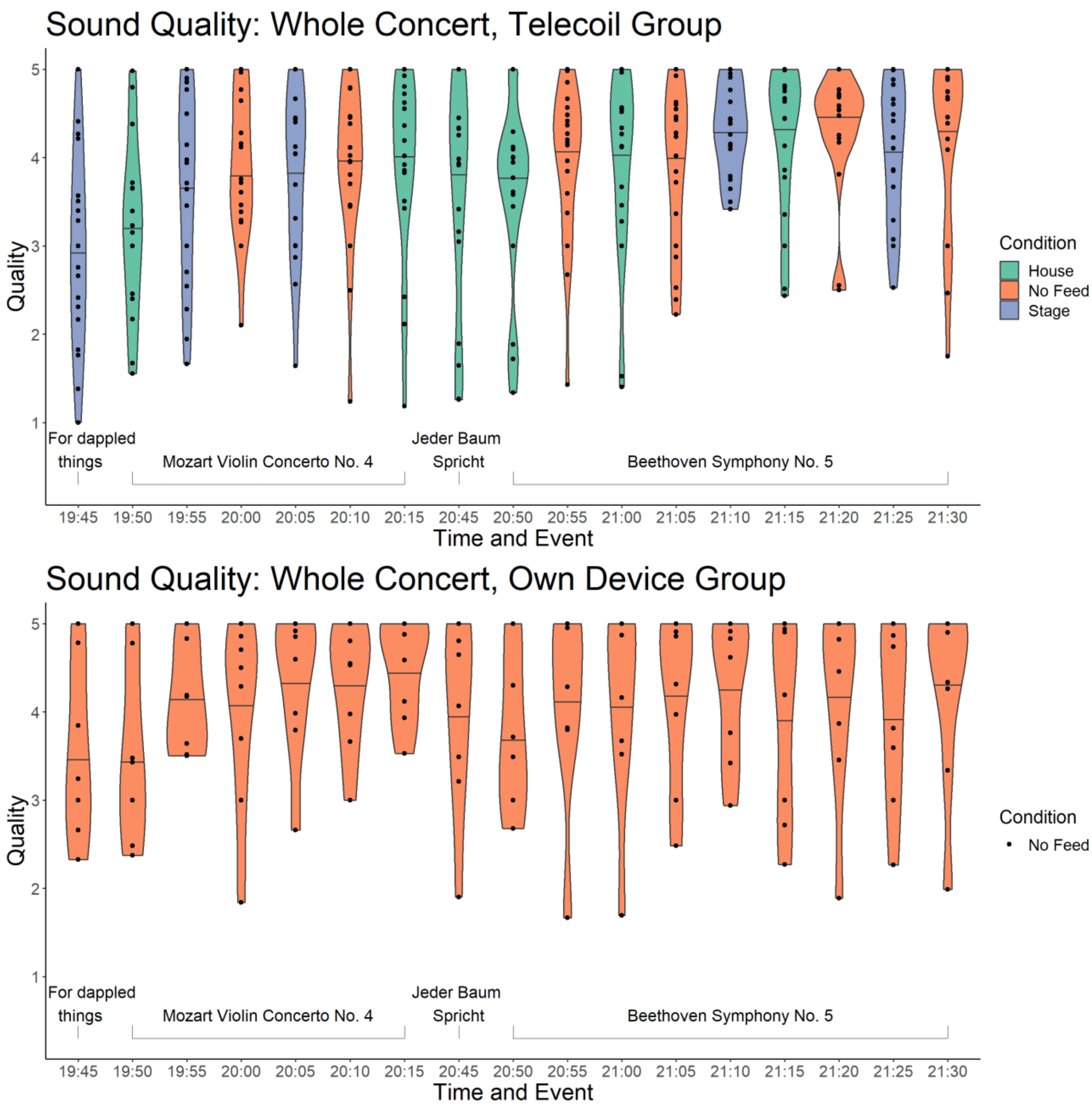
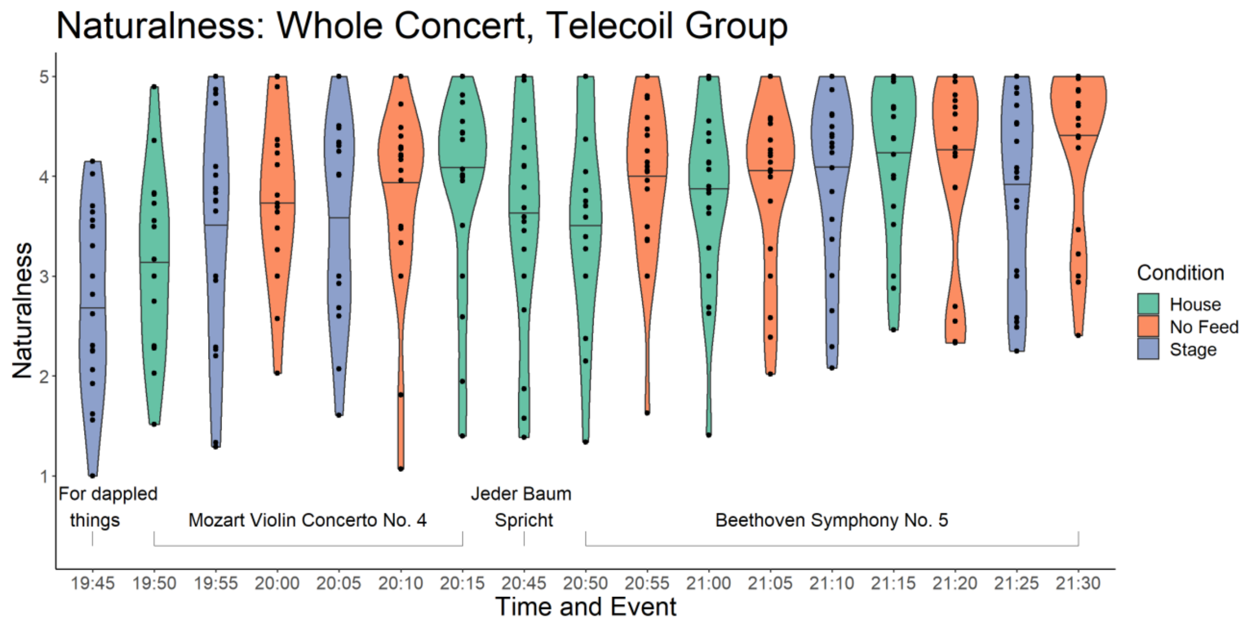


Figure 4.

Naturalness ratings for the Telecoil and Own Device Groups



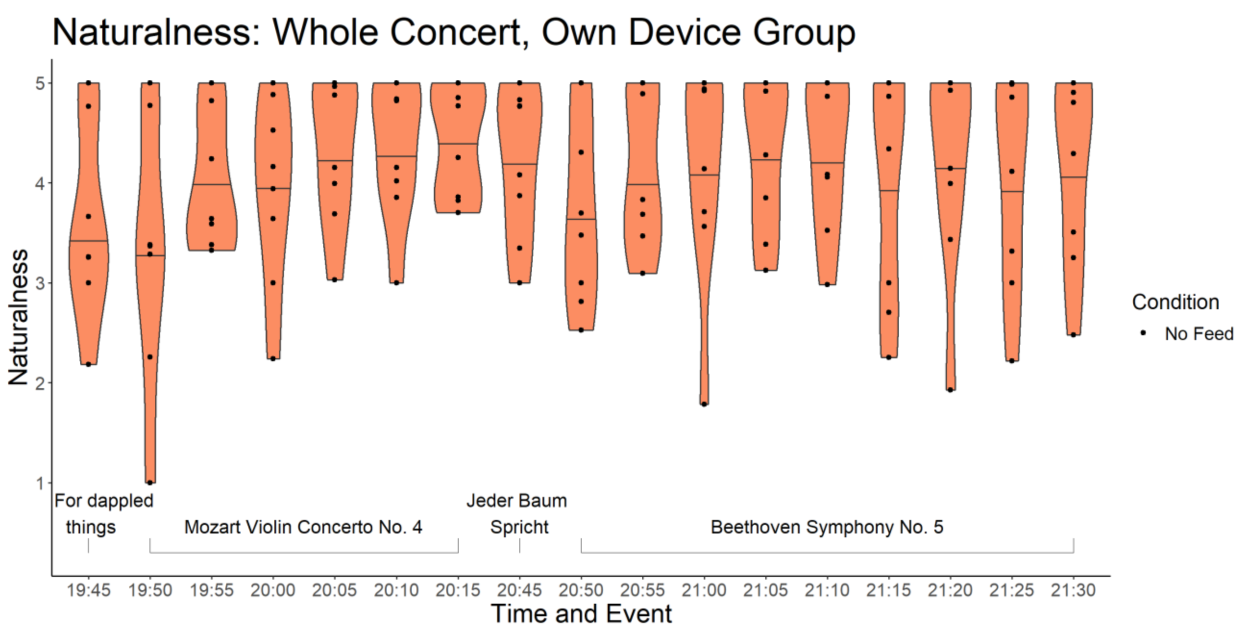
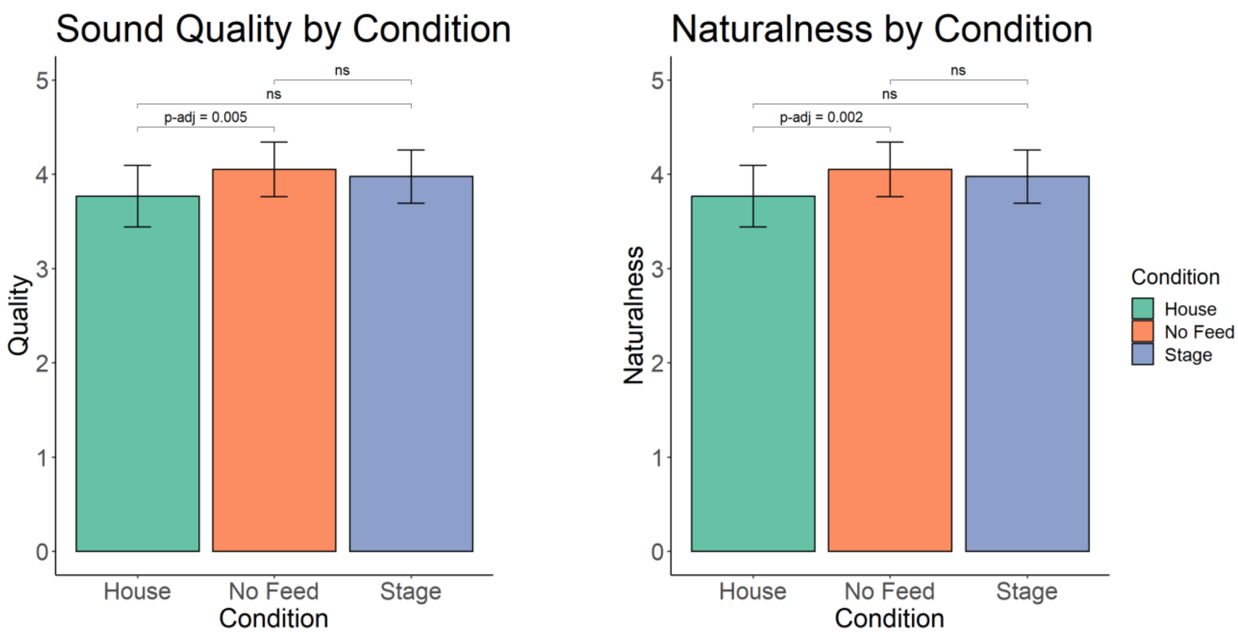


Figure 5.

Mean Quality and Naturalness Ratings by Condition for the Telecoil Group



Note. Error bars indicate 95% confidence intervals.

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