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The value of Headphone Accommodations in Apple AirPods Pro for managing speech-in-noise hearing difficulties of individuals with normal audiograms

Joaquin T. Valderrama[a,b,c,d,*], Jorge Mejia[a,e], Angela Wong[a], Nicky Chong-White[a,e], Brent Edwards[a,b]

[a] *National Acoustic Laboratories, Sydney, Australia.*

[b] *Department of Linguistics, Macquarie University, Sydney, Australia.*

[c] *Department of Signal Theory, Telematics and Communications, University of Granada, Granada, Spain*

[d] *Research Centre for Information and Communications Technologies (CITIC-UGR), University of Granada, Granada, Spain*

[e] *School of Computing, Macquarie University, Sydney, Australia.*

* Corresponding author

Joaquin T. Valderrama
Department of Signal Theory, Telematics and Communications
Escuela Técnica Superior de Ingenierías informática y de Telecomunicaciones
C/ Periodista Daniel Saucedo Aranda, s/n
18014, Granada, Spain

Phone: +34 648 457 023
Email addresses: jvalderrama@ugr.es, joaquin.valderrama@mq.edu.au.

ORCID codes:
Author 1: 0000-0002-5529-8620
Author 2: 0000-0002-9624-2842
Author 3: 0000-0002-1292-0256
Author 4: 0000-0001-5114-2429
Author 5: 0000-0003-0111-1899

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Abstract

Objective: To investigate the extent to which Headphone Accommodations in Apple AirPods Pro attend to the hearing needs of individuals with normal audiograms who experience hearing difficulties in noisy environments.

Design: Single-arm interventional study using acoustic measures, speech-in-noise laboratory testing, and real-world measures via questionnaires and ecological momentary assessment.

Study sample: Seventeen normal-hearing individuals (9 female, 21—59 years) with self-reported hearing-in-noise difficulties.

Results: Acoustic measures showed that, relative to unaided, AirPods Pro provided a SNR advantage of +5.36 dB. Speech intelligibility performance in laboratory testing increased 11.8% with AirPods Pro, relative to unaided. On average, participants trialling AirPods Pro in real-world noisy venues reported that their overall hearing experience was *a bit better* than without them. Five participants (29%) reported that they would continue using AirPods Pro in the future. The most relevant barriers that would discourage their future use were limited hearing benefit, discomfort, and stigma.

Conclusions: Occasional use of AirPods Pro may help some individuals with normal audiograms ameliorate their speech-in-noise hearing difficulties. The identified barriers may inspire the development of new technological solutions aimed at providing an optimal management strategy for the hearing difficulties of this segment of the population.

Keywords

Hearables; Hidden hearing loss; Over-the-counter hearing aids; Listening effort; Communication difficulties.

Introduction

Around 10—12% of the people who visit a hearing clinic and report more-than-expected hearing difficulties in noisy environments present normal pure-tone audiometric thresholds (Kumar et al., 2007; Pryce and Wainwright, 2008; Tremblay et al., 2015). This type of hearing deficit is sometimes referred to in the literature as *hidden hearing loss* (HHL, Schaette and McAlpine, 2011; Valderrama et al., 2022), due to the absence of a standardised diagnostic and management clinical protocol (Oxenham, 2016; Plack et al., 2014, 2016; Valderrama et al., 2018; Verhulst et al., 2016). For clarity, the HHL term is used in this paper according to the definition provided by the World Health Organisation in its 2021 World Report on Hearing: <<*the condition where an individual experiences common symptoms associated with noise-related auditory damage, such as difficulty in hearing in noise, and that is undetectable on pure-tone audiometry*>> (World Health Organisation, 2021).

Research conducted at the National Acoustic Laboratories (NAL, Sydney, Australia) following design thinking principles (Mealings et al., 2020) showed that HHL hearing difficulties have a negative impact on the quality of life of the people who experience them, with conversations in noisy environments often resulting in important information being missed, and requiring extra mental effort. Individuals with these hearing difficulties reported feeling frustrated and anxious about a potential misinterpretation of their reactions; which in many cases led to a change in their behaviour, progressively reducing their social encounters and increasing their risk of social isolation. For example, at an interview one participant responded: "*It just makes me feel disinclined to go out, and when I do, I tend to avoid restaurants and cafés and anything which is likely to be a crowd of people, unfortunately. It does take away some of the pleasure of being around people*". Furthermore, this study showed that this hearing problem also has a negative impact on the clinicians who attend these patients. Clinicians often report feeling frustrated— because the nature of patients' hearing problems cannot be determined through the available clinical tools; as well as disoriented and disempowered—since there is no standardized protocol or clinical guidelines for this population. Consequently, clinic appointments result in either no recommendation, leaving communication difficulties of patients untreated, or improvisation based on previous experience rather than scientific evidence. For example, one clinician disclosed: "*I quite often feel that I am not doing a really good job because they (clients) come in wanting an answer and I can't give it to them. It would be useful to have research that could lead to an evidence-based test battery, guidelines for management, and effective rehabilitation programs*". These findings support the need to define an efficient management strategy for the speech-in-noise hearing difficulties reported by individuals with normal audiograms.

A questionnaire survey investigating the most common approaches that audiologists used to attend to the hearing difficulties associated with HHL (Koerner et al., 2020) revealed that around 23% of the surveyed audiologists (n=157) used mild-gain hearing aids as their preferred rehabilitation strategy, despite the lack of evidence of these technologies addressing the hearing-in-noise difficulties associated with HHL. In fact, to date, only two studies have investigated the use of mild-gain hearing aids for this population (Roup et al., 2018; Singh and Doherty, 2020). Importantly, these studies showed that mild-gain hearing aids helped reduce hearing-in-noise handicap; however, only 3 out of 17 participants (i.e. 17%) in Roup et al. (2018) and 2 out of 10 participants (i.e. 20%) in Singh and Doherty (2020) reported being willing to continue using the hearing aids at the end of the trial, which indicates that these technologies remain suboptimal for the majority of people with HHL.

Edwards (2020) proposed a model anticipating which technologies would be preferred by different segments of the population who self-perceive hearing difficulties. This model predicted that individuals with hearing difficulties but normal audiograms would benefit from devices that enhanced the signal-to-noise ratio (SNR) or provided any improvement in understanding target speech; and that individuals from this segment of the population are potential candidates for *hearables*—emerging technologies not necessarily intended to compensate for hearing loss but to improve the hearing experience via directional microphones and advanced signal processing methods that attenuate background noise. This model is consistent with the findings reported by Mealings et al. (2020), where 62% of 233 participants with normal or near-normal audiograms reported they were 'ready and willing' to trial hearables as a potential intervention for their speech-in-noise hearing difficulties.

The objective of this study was to investigate the value of AirPods Pro hearables (Apple Inc., Cupertino, CA) for managing speech-in-noise hearing difficulties reported by individuals with normal audiograms. This study takes advantage of new accessibility features released in iOS 15 for the AirPods Pro to improve the hearing experience in noisy environments (Apple, 2022), including (i) *Conversation Boost*—technology that uses directional microphones and digital processing to enhance the voice of the person in front, thus facilitating face-to-face conversations in crowded or noisy environments; and (ii) *Ambient Noise Reduction*—digital processing that reduces background noise.

The value of AirPods Pro was evaluated via (i) acoustic measures, (ii) laboratory tests evaluating the benefit of AirPods Pro on speech-in-noise intelligibility and subjective workload (a term that encompasses self-perceived mental demand, performance, effort and frustration); (iii) real-world measures of different dimensions of the hearing experience trialling AirPods Pro in noisy venues using ecological momentary assessment tools; and (iv) both quantitative and open-ended questionnaires.

Materials and methods

Ethics and data sharing

The study protocols of this research were approved by the Hearing Australia Human Research Ethics Committee (Ref. HAHREC.2021-21). Consistent with the Findable, Accessible, Interoperable, and Reusable (FAIR) Data Principles (Wilkinson et al., 2016), the raw data of this research and Matlab (The Mathworks Inc., Natick, MA) scripts that re-generate the figures of this manuscript from the raw data are available as supplementary material in Appendix A.

Participants recruitment and inclusion criteria

Participants were recruited from the NAL participant database—an extensive list of people with different hearing profiles who have given their consent to be invited to participate in NAL research; flyers and posters in hearing clinics near the Australian Hearing Hub (Sydney, Australia); staff and students from Macquarie University (Sydney, Australia); and advertisements at the Macquarie University campus and on social media.

The requirements to participate in the study were (i) to be 18—70 years old; (ii) to be proficient in English; (iii) to have normal pure-tone audiometric thresholds, defined as a four-frequency average hearing loss (i.e. the mean hearing threshold at 0.5, 1, 2 and 4 kHz) better than or equal to 25 dB hearing level in both ears; and (iv) to report difficulty hearing speech in noisy environments, determined by a score greater than 7 in the Revised Hearing Handicap Inventory and Screening questionnaire (RHHI-S)—a validated questionnaire appropriate for screening self-perceived hearing handicap, where a score greater than 7 is associated with a risk of hearing loss (Cassarly et al., 2020).

Potential candidates interested in participating in the study were asked to complete the RHHI-S questionnaire, and a demographics questionnaire including questions about their age, gender, contact details, and English proficiency on a 5-point scale (beginner, intermediate, advanced, proficient and native). These questionnaires were administered via the REDCap software platform—a secure web application for building and managing online surveys and databases (Harris et al., 2009, 2019). Potential candidates that met the age, English proficiency, and self-reported hearing difficulties inclusion criteria were invited to attend to a 2-hour appointment at NAL. In this appointment, the hearing sensitivity of the potential candidates was characterised in terms of their pure-tone audiometric thresholds from 0.25 to 16 kHz using the AC40 clinical audiometer (Interacoustics A/S, Middelfart, Denmark). Potential candidates who met the pure-tone audiometric threshold inclusion criterion were formally invited to participate in the study and gave their written consent.

Participants

[Figure 1 around here]

Seventeen adults (9 female, 21—59 years, mean ± std = 41.1 ± 12.1 years) participated in the study. All participants were reimbursed for their time at the end of the study.

The boxplots in Figure 1 present the quartiles of the distributions of the pure-tone audiometric threshold across participants at each frequency for left and right ears. This figure shows that all participants had clinically normal hearing, and that they presented a large variability in extended high frequencies (i.e. at 12 and 16 kHz). In addition, tympanometry measures using the Interacoustics Titan tympanometer showed that all participants presented Type A tympanograms, with the exception of one participant who had Type As in the right ear and Type A in the left ear.

Participants' speech-in-noise hearing difficulties were measured via the *speech* dimension of the short form of the Speech, Spatial and Qualities of Hearing scale (SSQ12; Noble et al., 2013), i.e. the first five items of the SSQ12 questionnaire that evaluate speech understanding in situations with loud background noise, with several people involved in the conversation, and effects of selective or switching attention on a 0-to-10 point scale, where 0 represents 'severe hearing difficulties' and 10 is 'no hearing difficulties'. The mean score across participants on the *speech* subscale of the SSQ12 questionnaire was 5.2, consistent with their self-reported hearing difficulties.

AirPods Pro setup

Participants were given a pair of AirPods Pro (1st generation) that were set up so the audio was tuned based on their pure-tone audiogram. The hearing-related settings included *Transparency*

Mode enabled, *Headphone Accommodations* enabled, *Conversation Boost* (CB) enabled, and *Ambient Noise Reduction* (ANR) set to the maximum level. This configuration setup was selected to optimise the benefit of the devices for communication in noisy environments. Participants were not allowed to modify the setup of the devices in any part of the study in order to standardise the devices setup across participants. The detailed protocol of the AirPods Pro setup, including how the devices were personalised to the individual pure-tone audiometry of each participant, is provided as supplementary material in Appendix B (Section 1).

Real-ear measures

The sound delivered by AirPods Pro at the eardrum was measured via real-ear measurements using the Aurical Freefit (Natus Medical Inc., Middleton, WI), with probe microphone tubes inserted in the participants' left and right ear canal. The sound stimulus was the International Speech Test Signal (ISTS, Holube et al. 2010) —a signal that combines speech segments spoken by a female speaker in six different mother tongues (American English, Arabic, Chinese, French, German, and Spanish) reading 'The north wind and the sun'. This sound stimulus was delivered from a front speaker situated 1 meter from the participant. Measurements while wearing and while not wearing AirPods Pro provided the Real Ear Aided Gain (REAG) and Real Ear Unaided Gain (REUG), respectively. The Real Ear Insertion Gain (REIG) was obtained by subtracting REUG from REAG, i.e. REIG = REAG - REUG. Since none of the participants presented asymmetrical hearing loss (i.e. >15 dB difference between the 3-frequency average hearing loss from the left and right ears), measures from the two ears were averaged to form a single response per participant. Four test scenarios were measured: (i) Stimulus presented at 65 dB sound pressure level (SPL) and *Conversation Boost* enabled (i.e. CB-ON) on the AirPods Pro; (ii) stimulus at 55 dB SPL, CB-OFF; (iii) stimulus at 65 dB SPL, CB-OFF; and (iv) stimulus at 75 dB SPL, CB-OFF. *Ambient Noise Reduction* was disabled in all the real-ear measures. REIG measures were compared to the target amplification that would be provided by a hearing aid according to the NAL-NL2 prescription (Keidser et al., 2011).

Behavioural laboratory measures

Speech intelligibility with and without AirPods Pro was measured in a laboratory setting using the Beautifully Efficient Speech Test (BEST)—an Australian English speech-in-noise sentence test that uses morpheme-level scoring (Best et al., 2014, 2018). Background noise consisted of multi-talker continuous babble noise presented at a fixed level of 65 dB SPL from 16 speakers equally positioned in a circular array of 2.7 m diameter. Target speech were Bamford-Kowal-Bench (BKB) sentences naturally spoken by an Australian male talker, and were presented to the participant from the front speaker at different levels. Participants were seated in the centre of the speaker array, and were instructed to repeat back each of the presented sentences. The researcher scored the correctly understood morphemes from the control room. The BEST test was administered in 3 conditions: (condition 1) target-speech level varied using an adaptive method to estimate the SNR at which unaided participants presented 50% intelligibility (i.e., 50% speech-reception threshold, SRT-50); (condition 2) target-speech level fixed at SRT-50, participants being unaided; and (condition 3) target-speech level fixed at SRT-50, participants wearing the AirPods Pro. Condition 1 was always presented at the start of the test, and the order of conditions 2 and 3 was randomised for each participant. Two lists of 16 sentences were presented in each condition. Each condition used the same lists of sentences across participants, but the presentation order of the sentences was randomised.

At the end of conditions 2 and 3, participants were asked to rate their subjective workload via the NASA-TLX questionnaire (Hart and Staveland, 1988; Hart, 2006), responding to four questions about their *mental demand* ('how mentally demanding was the task?'), *performance* ('how successful were you in accomplishing what you were asked to do?'), *effort* ('how hard did you have to work to accomplish your level of performance?’), and *frustration* (‘how insecure, discouraged, irritated, stressed and annoyed were you’).

Real-world measures

Participants were asked to use AirPods Pro in real-world noisy situations where they usually struggle communicating with their peers, and rate different dimensions of their hearing experience via the NAL-Ecologically Momentary Assessment (NEMA) tool—a mobile application developed by NAL that was installed on the participants’ smartphone and allowed them to respond to a series of brief questions while they were using AirPods Pro as an assistive listening device in real-world situations. For these assessments, participants were instructed to have conversations in noisy venues, with the first 15 minutes unaided so they gained an understanding of their hearing experience without any help, and then to trial the AirPods Pro as an assistive listening device during the following 30 minutes. Immediately afterwards, participants were asked to respond to the multiple-choice NEMA questions (Q) below while they were in the noisy venue:

Q1. How would you rate your *overall hearing experience* with the AirPods Pro compared to not wearing them? a. Significantly better; b. A bit better; c. About the same; d. A bit worse; e. Much worse.

Q2. How would you rate your *speech understanding* with the AirPods Pro compared to not wearing them? a. Significantly better; b. A bit better; c. About the same; d. A bit worse; e. Much worse.

Q3. How would you rate your *participation* in the conversation with the AirPods Pro compared to not wearing them? a. Significantly better; b. A bit better; c. About the same; d. A bit worse; e. Much worse.

Q4. How would you rate your *emotional state* with the AirPods Pro compared to not wearing them? a. Much more confident; b. a bit more confident; c. About the same; d. A bit more frustrated; e. Much more frustrated.

Q5. How would you rate the *sound quality* of the AirPods Pro? a. Very good; b. Good; c. Neutral; d. Poor; e. Very poor.

Q6. How likely would you use the AirPods Pro in similar situations in the future? a. Very likely; b. Likely; c. Hard to say; d. Unlikely; e. Very unlikely.

Q7. What is the main *barrier* that would discourage you to use the AirPods Pro in a similar situation in the future? a. Limited hearing benefit; b. Uncomfortable to wear; c. Feeling embarrassed; d. Other; e. No significant barrier.

Questions 1 to 6 were Likert scales in which equal distance between each successive item was assumed, and following convention, a progressive numerical value was assigned to each scale in order to quantify the magnitude of the responses. In contrast, items in question 7 were treated as independent categories.

The NEMA App also captured acoustic features of the environment by processing sound recorded by the smartphone microphone while participants were completing the survey, including measuring the A-weighted background noise level in dBA, spectral envelope, entropy and reverberation. No audio signal was stored in order to preserve privacy.

Participants were asked to complete 10 surveys in different noisy venues during a 4-week period; and they were followed up weekly to track progress and to respond to any possible questions. At the end of the study, participants returned the AirPods Pro to NAL via post using a pre-paid satchel that was given to them in the NAL appointment.

End-of-study questionnaires

At the end of study, participants rated their satisfaction with AirPods Pro via the 'Satisfaction with Amplification in Daily Life' scale (SADL; Cox and Alexander, 1999)—a validated questionnaire originally designed to quantify satisfaction with hearing aids. This questionnaire was slightly modified to accommodate questions relevant to AirPods Pro devices, and some questions were omitted (e.g. those related to hearing aid repairs or to the whistling effect typically found in hearing aids). The modified version of the SADL questionnaire used in this study had 11 questions, which are presented as supplementary material in Appendix B (Section 2). The SADL Global score was obtained as described by Cox and Alexander (1999), i.e. by reversing the score of the questions in which lower score meant higher satisfaction, and by averaging the resulting scores from all the questions.

In addition, participants completed the OPEN-Q—a non-validated questionnaire developed by the authors consisting of six open-ended questions, where they could describe in their own words different dimensions of their experience using AirPods Pro as an assistive listening device. The six questions of the OPEN-Q were: (Q1) *To what degree do the AirPods Pro improve your hearing experience when communicating in acoustically challenging scenarios?* (Q2) *What are the positives of the AirPods Pro?* (Q3) *What are the most relevant negatives?* (Q4) *Have the AirPods Pro met your expectations? Which were your expectations?* (Q5) *Would you continue using the AirPods Pro as an assistive listening device in the future? Why/why not?* (Q6) *What are the main barriers that would discourage you to continue using the AirPods Pro In noisy environments?*

Acoustic Measures

Acoustic measures aimed to characterise the AirPods Pro acoustic benefit in the scenario of the laboratory speech-in-noise task, and were performed using the same protocol setup of the BEST test (defined in the *Behavioural laboratory measures* subsection), using a SNR of -3.5 dB (which corresponds to the mean SRT-50 across participants in the BEST test, and is a SNR that can be found in a challenging café or restaurant (Wu et al., 2018; Weisser et al., 2019)); and setting up the AirPods Pro with the audiogram that results from averaging the pure-tone hearing thresholds across participants. Sound recordings at the eardrum were obtained using real-ear measurements by a probe microphone tube inserted in the left ear of a participant seated in the centre of the array of speakers. Four conditions were tested: (condition 1) unaided; (condition 2) *Conversation Boost* enabled (CB-ON), *Ambient Noise Reduction* at maximum level (ANR-Max); (condition 3) CB-ON, ANR-Min; and (condition 4) CB-OFF, ANR-Max.

The acoustic benefit provided by AirPods Pro was defined in terms of SNR, measured using the inversion technique defined by Hagerman and Olofsson (2004). In this technique, two recordings were obtained using the same stimulus and background noise signals, but in the second recording the phase of the stimulus was inverted. This allowed the separation of speech from the noise by (i) subtracting the two recordings to estimate the target speech (i.e. [Noise + Speech] – [Noise – Speech] = 2*Speech); and (ii) adding the two recordings to estimate the noise (i.e. [Noise + Speech] + [Noise – Speech] = 2*Noise); thus enabling the calculation of the SNR. In order to effectively separate the two signals using this procedure, the AirPods Pro were conditioned to a steady state before the SNR was estimated. To relate the SNR to speech intelligibility, a series of weights at different frequencies defined by the speech intelligibility index (SII, ANSI S3.5—1997; Amlany et al., 2002; Killion et al., 2002) were applied to the SNR estimate resulting from the Hagerman and Olofsson (2004) inversion technique. The SII-weighted SNR advantage values across frequencies were averaged to obtain a single index which we will refer to as the SII-SNR advantage.

Results

Real-ear measures

[Figure 2 around here]

Figure 2 shows the averaged REIG across participants obtained for an acoustic stimulus presented at 65 dB SPL, with *Conversation Boost* enabled in AirPods Pro. This figure visually shows that, on average, AirPods Pro provide around +4 dB of amplification in the 400–4000 Hz frequency band. This figure also shows that the averaged REIG deviates from the target amplification that would be provided by a hearing aid following the NAL-NL2 prescription, providing higher amplification in the 400–3000 Hz frequency band, and lower amplification in the high frequencies, i.e. in the 5000–8000 Hz band. The REIG measures from each participant, along with REUG and REIG measures obtained with an acoustic stimulus presented at 55, 65, and 75 dB SPL with *Conversation Boost* disabled are presented as supplementary material in Appendix B (Section 3).

Acoustic measures

[Table 1 around here]

Table 1 shows the SII-SNR advantage obtained at the eardrum with AirPods Pro configured in different settings relative to the unaided condition. This table shows that, in the acoustic scenario of the BEST test, the combined effect of CB and ANR provides a SII-SNR benefit of +5.36 dB. Furthermore, this analysis showed that the isolated SII-SNR benefit provided by CB was +3.20 dB; and the benefit of ANR was +1.85 dB.

Behavioural laboratory measures

[Figure 3 around here]

Panel A of Figure 3 shows the percentage of correctly understood words in the BEST test per participant, with and without AirPods Pro. This figure shows that on average intelligibility increased from 54.6% when participants were unaided to 66.4% when they wore AirPods Pro. A paired *t*-test analysis revealed that this difference was statistically significant (p=4.7·10^{-5}). Furthermore, this figure shows that this intelligibility improvement was consistent across most of the participants, with only 2 participants performing slightly worse with AirPods Pro relative to the unaided condition.

Panel B in Figure 3 presents the subjective workload associated with the BEST test, as determined by four dimensions of the NASA-TLX scale: mental demand, performance, effort and frustration. Paired *t*-tests demonstrated that AirPods Pro reduced the mental demand of the task (p=0.008), improved participants' performance (p=0.04), and reduced their self-perceived effort (p=0.004). The effect of AirPods Pro in reducing frustration was not statistically significant (p=0.18).

Real-world measures

[Figure 4 around here]

The NEMA-survey database consisted of 174 surveys for this study, which makes an average of 10.2 surveys per participant. The number of surveys per participant ranged from 7 to 15 surveys per participant. Forty-nine surveys were taken in a café/restaurant, 35 in a party or gathering at home, 12 in a bar/pub, 33 in a shopping centre, and 45 in other venues. Seventy-four surveys were completed on a one-to-one conversation, 77 surveys in a group from 3 to 6 people, and 23 surveys in a group with more than 6 people.

Figure 4.A shows the histogram of the A-weighted background noise level of the environments where participants trialled the AirPods Pro. This figure shows that most of the surveys (81%) were conducted in sound environments above 70 dBA, thus indicating that the environments attended by the participants presented an acoustic challenge for communication. The remaining acoustic features captured by NEMA (i.e. spectral envelope, entropy, reverberation, etc.) are available as supplementary material in Appendix A.

Statistical analyses using linear mixed-effects models with the background noise level, the location and the number of people in the group as predictor variables, and participants as random effect, showed that none of the predictor variables had a statistically significant effect on the outcomes of any of the questions of the NEMA surveys. This result allowed us to reduce the dimensionality of the database by averaging the survey scores from each participant, thus obtaining one mean score per participant.

Panels B to G in Figure 4 show histograms of the mean score per participant to the first six questions of the NEMA survey. The average score across participants is numerically presented on top of the dotted line; and the *p*-value in bracket presents the statistical significance of a *t*-test that evaluates whether the average score is different from 3.0, i.e. the score that represents neutrality or equivalent experience to not using AirPods Pro. These panels show that, on average, participants found that (i) AirPods Pro provided them with a bit better overall hearing experience (panel B), (ii) their intelligibility in noise was a bit better when they were wearing AirPods Pro (panel C), (iii) they found themselves participating a bit more in conversations (panel D), and (iv) the sound quality of the AirPods Pro was perceived as *good* (panel F). However, the question about AirPods Pro improving the emotional state of the participants led a to a large variability on the responses, and on average, participants felt about the same while wearing and while not wearing the AirPods Pro (panel E). Consistent with this outcome, at group level it is not possible to conclude that participants would continue using AirPods Pro in similar situations in the future (panel G). Five out of 17 participants (i.e. 29%) responded that it would be *likely* or *very likely* to keep using AirPods Pro as an assistive listening device.

Panel H presents the frequency occurrence of different barriers that would discourage participants to keep using AirPods Pro in similar situations in the future. The most commonly reported barrier was about AirPods Pro providing limited hearing benefit (55 surveys), followed by comfort issues (32 surveys) and stigma (27 surveys). Twenty-three surveys identified *other* barriers (but they were not specified), and 37 surveys found no barriers.

End-of-study questionnaires

[Figure 5 around here]

Figure 5 presents the histogram of the SADL Global score. This figure shows that participants' global satisfaction with the amplification provided by AirPods Pro was in the range of *somewhat* satisfied. Only 2 participants reported to be *considerably* or *greatly* satisfied. This figure also shows that the average score across participants (i.e. 3.34 on a scale 1 to 7) is lower than the satisfaction score that would be expected from hearing aid users, as determined by normative data obtained from a study conducted on 365 hearing aid users (Cox and Alexander, 1999). It should be noted that the comparison of SADL results with normative data shall be done with some degree of caution, as the SADL questionnaire used here was a modified version of the original version (which involved 11 questions selected from the original 15 items). Interestingly, participants' satisfaction with AirPods Pro correlated with the overall hearing experience scored in the NEMA surveys ($r=0.55$, $p=0.02$). This correlation figure is presented as supplementary material in Appendix B (Section 4).

Participants also responded to six open-ended questions from the OPEN-Q. The full responses from all the participants to each question are presented as supplementary material in Appendix B (Section 5).

To the question ‘*To what degree do the AirPods Pro improve your hearing experience when communicating in acoustically challenging scenarios?*’ (Question 1), (i) seven participants (41%) responded ‘*not much*’—for example, one participant responded: “*There is some improvement but it is minimal even when you increase the volume on them. I also found that the AirPods would sporadically muffle some voices when in a large group. I wasn’t overly impressed with them as an assistive listening device. When it is windy (e.g. for outside events) the AirPods Pro actually make the wind noisier and negatively impact your conversations*”; (ii) seven participants (41%) answered that their experience depended on the ambient sound around them—one participant said: “*My experience was inconsistent. In one-on-one situations they performed better compared to group gatherings. In other occasions, sounds like the rubbing of my hair against the AirPods Pro and the sound of my chewing were amplified, whereas other background sounds were not*”; and (iii) the remaining 3 participants (18%) had a positive experience—for example, one participant answered: “*I could hear voices much more clearly in close proximity as well as some distance away. I felt more engaged in the conversations because I could hear better. The ability to hear people at the dinner table at a noisy restaurant is probably the most beneficial*”.

When asked about the positives of AirPods Pro (Question 2), participants highlighted that they improved speech-in-noise hearing in some scenarios, technical features such as sufficient runtime, comfort, easy pairing with iPhone, easy to use, multi-purpose (they work for noise reduction, listen to music, make calls, etc.), beautiful design, and AirPods Pro being small and unobtrusive. For example, one participant responded: “*Easy and comfortable to wear, without needing to insert something small into my ear canal or irritation around the ear lobe. Inexpensive, multi-purpose (I could also use it to block out sound, listen to music, make calls in very good quality across all uses). The settings and features available on iOS were quite intuitive to use and if was to delve into settings more, it would allow me to more tailor the sound to what I might need.*”

Participants were also asked to comment on the most relevant negatives of AirPods Pro (Question 3). They mentioned (i) sound-quality issues, such as they provide an unnatural amplification of background and wind noises and hearing their own voice, walking or chewing through bone-conduction; (ii) comfort and functionality issues, like they were uncomfortable to wear or could easily get lost; (iii) the limited value they provide in communicating in noise; and (iv) societal and stigma issues, due to AirPods Pro not being generally accepted as an assistive listening device—which at times made them look unsociable and disconnected from the conversation. One participant commented: "*I did not feel at all embarrassed wearing them, but a few people asked me about them and why I was wearing them. In the trial it was easy to explain the scientific nature of the trial, but this might become irritating if long term use. It was potentially perceived by others that you were listening to music or doing other things whilst in a group or conversation. I don't think their hearing correction worked so well outside, in a loudish area on a beach with plenty of ambient environmental noise*".

The fourth question of the OPEN-Q was about their expectations. Participants expected AirPods Pro to help them hear better in noisy places, participate more in conversations, to be comfortable to wear, easy to use, to help them focus on one-on-one conversations, and that AirPods Pro would provide a natural sound. Nine participants (53%) responded that the AirPods Pro did not meet their expectations due to insufficient attenuation of background noise, unnatural amplification of surrounding noises, strong occlusion effect, and uncomfortable fitting of the devices in the ear. For example, one participant mentioned: "*I thought they would be far more helpful in improving my ability to communicate in background noise settings so I was really looking forward to trying them out*". Five participants (29%) responded that their expectations were met on some occasions, since conversations were not always clearer and they faced important social challenges. For example, one participant disclosed: "*I expected good quality sounds—which were met, however I did also expect more focus on the sounds closest to me (i.e. the person that I was conversing with would be louder) in order to be able to contribute more to* *the conversation*". Three participants (18%) responded that AirPods Pro met their expectations. For example, one participant said: "*I expected the AirPods Pro to be potentially better than hearing aids for this application. In terms of sound quality, I was impressed at their range compared to a hearing aid. The AirPods Pro felt like a true competitor or replacement for a traditional hearing aid. The ability to click a button and adjust detailed parameters (in a non-test situation) was impressive*".

Importantly, 12 participants (71%) responded that they would not continue using AirPods Pro in similar situations in the future (Question 5). The most relevant reasons were social factors, not enough or inconsistent hearing benefits, discomfort and embarrassment. For example, one participant mentioned: "*I would not use them in conversations. People think that you are ignoring them if they see you using them and the impact on the quality of the conversation is not significant*". The remaining 5 participants (29%) said that they would continue using them as an assistive listening device, but two of them also acknowledged the stigma barrier in social gatherings. For example, one participant reported: "*I would continue using AirPods with family and friends in group environment and / or work mates and associates in a work environment who know the purpose of the AirPods. Explaining the purpose of the AirPods would be problematic for me in most other environments where associating with people I am not directly associated with*".

Finally, the responses to the question about barriers that would discourage them from using AirPods Pro in noisy environments (Question 6) were consistent with previous statements, highlighting social factors (i.e. people in the conversation thinking they are being ignored), limited hearing benefit, and uncomfortable to wear for a long period of time.

Discussion

This study aimed to investigate the value of AirPods Pro for managing speech-in-noise hearing difficulties reported by individuals with normal audiograms. To approach this objective, (i) real-ear measurements and acoustic measures characterised the sound processing features of the devices; (ii) laboratory measures evaluated speech-in-noise intelligibility and subjective workload in a controlled and standardised sound environment; and (iii) collected ratings of everyday listening experiences via the NAL-Ecological Momentary Assessment tool (NEMA) and questionnaires evaluated the value of AirPods Pro in improving the hearing experience in acoustically-challenging venues.

Acoustic measures showed that *Conversation Boost* and *Active Noise Reduction* features led to a SII-SNR advantage of +5.36 dB for a talker situated 1 meter in front of the listener in a noisy environment with diffuse speech babble all around the listener. This SNR advantage is the result of the combined effect of the directivity provided by the directional microphones, the background noise reduction resulting from advanced digital signal processing, and the approximately 4 dB gain provided by the devices in the 400—4000 Hz frequency band, as shown in Figure 2 from real ear measures. The +5.36 dB SII-SNR advantage measure is comparable to the 3-to-6 dB SNR benefit expected when listening to a frontal talker in noise using directional microphones in hearing aids (Ricketts, 2001).

Three considerations should be noted regarding the acoustic measures of this study. First, the SII-SNR advantage reported here was estimated in one specific scenario. The selected acoustic scenario is typically used to measure directional microphones in hearing aids, and aimed to reproduce the behavioural speech-in-noise laboratory test of this study. Additional acoustic measures would be required to provide a generalised characterisation of the AirPods Pro acoustic benefit in a broad range of environments. Second, the SII-SNR advantages reported in this study show the acoustic benefit of CB and ANR features against the unaided condition—which is appropriate to respond to the main research question of the study. Additional acoustic measures conducted by the authors replicated these findings using a basic configuration of AirPods Pro as a baseline (i.e. CB and ANR disabled; Chong-White et al., 2022). These additional measures showed that, when a mild-to-moderate sloping hearing loss profile was used, the SII-

SNR advantages of CB, ANR, and CB+ANR were 4.51 dB, 2.05 dB, and 5.62 dB, respectively. These results indicate that both the unaided condition and a basic configuration of AirPods Pro (CB and ANR disabled) provide a similar baseline. Last, in addition to the SII-SNR metric used here, the literature provides different objective speech quality and intelligibility prediction methods, such as the short-term objective intelligibility (Taal et al., 2011). The use of SII-SNR in this study is appropriate, as it is designed specifically for individuals without hearing loss. Other methods have been proposed for individuals with hearing loss, such as the hearing aid speech perception index (Kates and Arehart, 2014). For a comparison of advantages and limitations of a broad range of existing methods under different environmental conditions, the reader is referred to Falk et al. (2015).

Behavioural laboratory measures showed that the AirPods Pro provided a 11.8% intelligibility improvement, increasing from 54.6% when participants were unaided to 66.4% when they wore AirPods Pro. This speech-in-noise intelligibility improvement was, however, lower than expected. For a SNR benefit of +3.2 dB provided by the Conversation Boost feature (the SNR benefit obtained from Ambient Noise Reduction is not considered here, as noise-reduction algorithms generally improve speech quality but contribute little to improving speech intelligibility (Hu and Loizou, 2007)), an improvement of around 30% in intelligibility would be expected (Best et al., 2014, 2018; Ricketts, 2001). In comparison to other studies, an improvement of 11.8% in speech-in-noise intelligibility corresponds to approximately 1 dB of SNR benefit (Best et al., 2014, 2018; Ricketts, 2001), which is comparable to the benefits of conventional noise reduction systems whereby the SNR measured is higher than the intelligibility improvement (Hu and Loizou, 2007). A plausible explanation to these results is that individuals with normal hearing but speech-in-noise hearing problems may present shallower intelligibility psychometric functions than those with hearing loss wearing hearing aids, thus receiving lower-than-expected benefit from the SNR improvement (MacPherson and Akeroyd, 2014).

Consistent with the small speech-intelligibility improvement observed in laboratory measures, participants perceived that AirPods Pro reduced the mental demand of the behavioural laboratory task by 8%, assisted them in improving their speech-in-noise intelligibility (6% improvement), and reduced their listening effort by 8%. Furthermore, the first three questions of the real-world NEMA surveys showed, at group level, that participants rated their overall hearing experience, their level of speech understanding in noise, and their participation in conversations *a bit better* with the AirPods Pro than without them.

Despite the small benefit, 5 out of 17 participants (i.e. 29% of the tested population) reported that they would be willing to continue using AirPods Pro for improving their communication in noisy situations. Although there might be a difference between what participants report they would do and what they finally do, this potential adoption rate is slightly higher than the 26% hearing aids adoption rate amongst people with hearing loss (Bisgaard and Ruf, 2017; Dillon et al., 2020). On the other hand, the remaining 71% of the participants flagged important concerns that would discourage their future use of AirPods Pro during conversations in acoustically-challenging scenarios, including (i) AirPods Pro providing a limited hearing benefit, (ii) stigma and embarrassment, and (iii) discomfort.

Limited hearing benefit was the most reported barrier to keep using AirPods Pro as an assistive listening device, reported by 31.6% of the total NEMA surveys. Open-ended questions from the OPEN-Q highlighted the negative impact on the quality of conversations derived from (i) the unnatural amplification of high-frequency sound sources such as wind, car brakes, or the sound of a bus engine; (ii) self-hearing of certain noises through bone conduction such as chewing, walking, or the sound of their own voice; and (iii) not enough attenuation of background noise. Therefore, future releases of AirPods Pro could consider using microphones with a higher directionality, aimed at providing more attenuation of the background noise. Further, future AirPods Pro releases may also consider improving the gain provided to listeners by prescribing gain functions that better match NAL-NL2 targets, as well as empowering individuals with finetuning functions that enable them to self-adjust the devices for a more personalised listening experience.

Discomfort was the second most-referenced barrier in the NEMA surveys, shown in 18.4% of the surveys. Three participants consistently indicated that their major concern was that AirPods Pro were *uncomfortable to wear* or *did not fit properly*, and four participants found comfort to be a problem but did not reported it as frequently. This means that less than half of the cohort reported comfort issues, while the remaining 10 participants did not. In fact, comfort was mentioned as one of the positives of AirPods Pro by some of the participants. This indicates a large inter-subject variability in terms of comfort—meaning that for some participants the AirPods Pro design fitted well within their ears, but for others the fitting was suboptimal. A possible way to overcome this is to use personalised coupling to the ears, that may include earmolds—an approach that is well established in the hearing aid industry and is emerging in the hearables landscape.

Feeling uncomfortable or embarrassed was the third most identified barrier using AirPods Pro while in conversations with other people. This barrier was reported in 15.5% of the total surveys from 10 different participants. The OPEN-Q showed that several participants reflected that AirPods Pro are not generally seen as an assistive listening device, and that wearing them often required having to give explanations to the people in the conversation. This result highlights the need for advertising campaigns that promote the hearing accessibility capabilities of AirPods Pro, beyond their functionality to listen to music and respond to phone calls. It is expected that this barrier shall decrease over time, as the use of hearables as assistive listening devices becomes more common and widespread by the general community.

Taken as a whole, the importance of this study is twofold. On the one hand, the methodologies used in this study can be applied to evaluate the efficacy and acceptability of new emerging technologies aimed at improving hearing experiences in noisy places. On the other, the quantitative and qualitative measures of the value of AirPods Pro can assist in the design of an evidence-based optimal treatment strategy for speech-in-noise hearing problems perceived by individuals with normal audiograms. The barriers for using AirPods Pro as an assistive listening device identified in this study are similar to those typically reported by people with hearing loss regarding entry models of hearing aids (Meyer and Hickson, 2012), but unlike hearing aids, AirPods Pro are not designed for rehabilitation, and an evidence-driven prescription is not yet available. Despite this limitation, the present study has shown that occasional use of AirPods Pro may help some listeners to overcome difficulties they encounter in everyday listening situations, and in doing so, AirPods Pro may offer an inexpensive alternative to hearing aids in attending to speech-in-noise intelligibility problems of individuals with normal audiograms. To this respect, the fact that around 30% of the participants reported that they would continue using the AirPods Pro to have a better hearing experience in noisy places indicates that this technology is a viable option for some individuals with normal audiograms but speech-in-noise hearing problems. However, participants accepting this technology (when tested using the prescription-based protocol defined in this study) are still a minority, and new research is required to develop innovative solutions that overcome the barriers identified in this study in order to improve the hearing experience and usability of AirPods Pro.

Future research could aim to identify the unique features that characterise those who perceive a higher value of this technology, in an attempt to provide evidence-based guidelines to clinical audiologists about the segment of the population that is expected to benefit the most from this technology. Another element that future research could consider is to allow participants to fine-tune the AirPods Pro setup. In the present study the configuration setup of AirPods Pro was standardised across participants (i.e. audio tune was personalised to their audiogram, Transparency mode was enabled, Conversation Boost was enabled, and Ambient Noise Reduction was set at maximum level), and participants were instructed to not change the AirPods Pro configuration in any of the tests. While this approach facilitated interpretability of results as a function of a specific *Headphone Accommodation* configuration, future research could investigate whether speech-in-noise intelligibility, self-perceived hearing difficulties, and satisfaction with AirPods Pro improve if participants are given the opportunity to personalise and self-adjust the settings of the devices, as shown in previous studies related to self-fitting hearing aids in individuals with hearing loss (Keidser and Convery, 2018). Further, provided the potential of the first generation of Apple AirPods Pro to improve speech-in-noise understanding in some participants with normal audiograms, and considering the capability of these earbuds to customise headphone audio using an audiogram, future research could investigate whether subsequent generations of Apple AirPods Pro help reduce real-world hearing-in-noise difficulties in a population with mild hearing loss.

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Data Accessibility Statement

The raw data of this research and Matlab scripts that re-generate the figures are available as supplementary material in Appendix A.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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ORCID iD

Joaquin T. Valderrama: https://orcid.org/0000-0002-5529-8620
Jorge Mejia: https://orcid.org/0000-0002-9624-2842
Angela Wong: https://orcid.org/0000-0002-1292-0256
Nicky Chong-White: https://orcid.org/0000-0001-5114-2429
Brent Edwards: https://orcid.org/0000-0003-0111-1899

Supplementary material

Supplemental data for this article can be accessed online at [URL].

References

American National Standards Institute. ANSI S3.5-1997. Methods for the calculation of the speech intelligibility index. New York: Acoustical Society of America, 1997.

Amlany A.M., Punch J.L., Ching T.Y.C. (2002) Methods and applications of the audibility index in hearing aid selection and fitting. Trends in Amplification 6: 81—129. Doi: 10.1177/108471380200600302.

Apple. (2022) Hearing accessibility features. Retrieved March 19, 2022, from https://www.apple.com/au/accessibility/hearing/

Best V., McLelland M., Dillon H. (2014) The BEST (Beautifully Efficient Speech Test) for evaluating speech intelligibility in noise. XXXII World Congress of Audiology (May 3—7, Brisbane, Australia).

Best V., Keidser G., Freeston K., Buchholz J.M. (2018) Evaluation of the NAL Dynamic Conversations Test in older listeners with hearing loss. International Journal of Audiology 57: 221—229. Doi: 10.1080/14992027.2017.1365275.

Bisgaard N., Ruf S. (2017) Findings from EuroTrak surveys from 2009 to 2015: Hearing loss prevalence, hearing aid adoption, and benefits of hearing aid use. American journal of audiology 26: 451—461. Doi: 10.1044/2017_AJA-16-0135.

Cassarly C., Matthews L.J., Simpson A.N., Dubno J.R. (2020) The revised hearing handicap inventory and screening tool based on psychometric reevaluation of the hearing handicap inventories for the elderly and adults. Ear and Hearing 41: 95—105. Doi: 10.1097/AUD.0000000000000746.

Chong-White N., Mejia J., Valderrama J., Edwards B. (2022) Evaluation of Apple AirPods Pro with Conversation Boost and Ambient Noise Reduction for people with hearing loss in noisy environments. The Hearing Review, March 2022. Available at: https://hearingreview.com/hearing-products/hearing-aids/psap/apple-airpods-pro-for-people-with-hearing-loss-in-noisy-environments.

Cox R.M., Alexander G.C. (1999) Measuring satisfaction with amplification in daily life: The SADL scale. Ear and Hearing 20: 306—320. Doi: 10.1097/00003446-199908000-00004.

Dillon H., Day J., Bant S., Munro K.J. (2020) Adoption, use and non-use of hearing aids: a robust estimate based on Welsh national survey statistics. International Journal of Audiology 59: 567—573. Doi: 10.1080/14992027.2020.1773550.

Edwards B. (2020) Emerging Technologies, Market Segments, and MarkeTrak 10 Insights in Hearing Health Technology. Seminars in Hearing 41: 37—54. Doi: 10.1055/s-0040-1701244.

Falk T.H., Parsa V., Santos J.F., Arehart K., Hazrati O., Huber R., Kates J.M., Scollie S. (2015) Objective quality and intelligibility prediction for users of assistive listening devices. IEEE Signal Processing Magazine 32, 114—124. Doi: 10.1109/MSP.2014.2358871.

Hagerman B., Olofsson A. (2004) A method to measure the effect of noise reduction algorithms using simultaneous speech and noise. Acta Acustica united with Acustica 90: 356—361.

Harris P.A., Taylor R., Thielke R., Payne J., Gonzalez N., Conde J.G. (2009) Research electronic data capture (REDCap) – A metadata-driven methodology and workflow process for providing translational research informatics support. Journal of Biomedical Informatics 42: 377—381. Doi: 10.1016/j.jbi.2008.08.010.

Harris P.A., Taylor T., Minor B.L., Elliott V., Fernandez M., O'Neal L., McLeod L., Delacqua G., Delacqua G., Kirby J., Duda S.N., REDCap Consortium (2019) The REDCap consortium: Building an international community of software platform partners. Journal of Biomedical Informatics 95: 103208. Doi: 10.1016/j.jbi.2019.103208.

Hart S.G., Staveland L.E. (1988) Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. Advances in Psychology 52: 139—183. Doi: 10.1016/S0166-4115(08)62386-9.

Hart S.G. (2006) NASA-Task Load Index (NASA-TLX); 20 Years Later. Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting 50: 904-908. Doi: 10.1177/154193120605000909.

Holube I., Fredelake S., Vlaming M., Kollmeier, B. (2010) Development and analysis of an International Speech Test Signal (ISTS). International Journal of Audiology 49: 891—903. Doi: 10.3109/14992027.2010.506889.

Hu Y., Loizou P.C. (2007) A comparative intelligibility study of single-microphone noise reduction algorithms. The Journal of the Acoustical Society of America 122: 1777. Doi: 10.1121/1.2766778.

Kates J.M., Arehart K.H. (2014) The hearing-aid speech perception index (HASPI). Speech Communication 65, 75—93. Doi: 10.1016/j.specom.2014.06.002.

Keidser, G., Convery, E. (2018). Outcomes with a self-fitting hearing aid. Trends in Hearing 22, 2331216518768958. Doi: 10.1177/2331216518768958.

Keidser G., Dillon H., Flax M., Ching T., Brewer S. (2011) The NAL-NL2 prescription procedure. Audiology Research 1: e24. Doi: 10.4081/audiores.2011.e24.

Killion M.C. (2002) New thinking on hearing in noise: A generalised articulation index. Seminars in Hearing 23: 57—76. Doi: 10.1055/s-2002-24976.

Koerner, T.K., Papesh, M.A., Gallun, F.J. (2020). A questionnaire survey of current rehabilitation practices for adults with normal hearing sensitivity who experience auditory difficulties. American Journal of Audiology 29, 738-761. Doi: 10.1044/2020_AJA-20-00027.

Kumar G., Amen F., Roy D. (2007) Normal hearing tests: Is a further appointment really necessary? Journal of the Royal Society of Medicine 100: 66. Doi: 10.1177/014107680710000212.

MacPherson A., Akeroyd M.A. (2014) Variations in the slope of psychometric functions for speech intelligibility: A systematic survey. Trends in Hearing 18: 2331216514537722. doi: 10.1177/2331216514537722.

Mealings K., Yeend I., Valderrama J.T., Gilliver M., Pang J., Heeris J., Jackson P. (2020) Discovering the unmet needs of people with difficulties understanding speech in noise and a normal or near-normal audiogram. American Journal of Audiology 29: 329—355. Doi: 10.1044/2020_AJA-19-00093.

Meyer C., Hickson L. (2012) What factors influence help-seeking for hearing impairment and hearing aid adoption in older adults? International Journal of Audiology 51: 66—74. Doi: 10.3109/14992027.2011.611178.

Noble W., Jensen N.S., Naylor G., Bhullar N., Akeroyd M.A. (2013) A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: The SSQ12. International Journal of Audiology 52: 409—412. Doi: 10.3109/14992027.2013.781278.

Oxenham A.J. (2016) Predicting the perceptual consequences of hidden hearing loss. Trends in Hearing 20, 2331216516686768. Doi: 10.1177/2331216516686768.

Plack C.J., Barker D., Prendergast G. (2014) Perceptual consequences of "hidden" hearing loss. Trends in Hearing 18: 2331216514550621. Doi: 10.1177/2331216514550621.

Plack C.J., Léger A., Prendergast G., Kluk K., Guest H., Munro K.J. (2016) Toward a diagnostic test for hidden hearing loss. Trends in Hearing 20: 2331216516657466. Doi: 10.1177/2331216516657466.

Pryce H., Wainwright D. (2008) Help-seeking for medically unexplained hearing difficulties: A qualitative study. International Journal of Therapy and Rehabilitation 15: 343—349. Doi: 10.12968/ijtr.2008.15.8.30818.

Ricketts T.A. (2001) Directional hearing aids. Trends in Amplification 5, 139—176. Doi 10.1177/108471380100500401.

Roup, C.M., Post, E., Lewis, J. (2018). Mild-gain hearing aids as a treatment for adults with self-reported hearing difficulties. Journal of the American Academy of Audiology 29, 477-494. Doi: 10.3766/jaaa.16111.

Schaette R., McAlpine D. (2011) Tinnitus with a normal audiogram: Physiological evidence for hidden hearing loss and computational model. The Journal of Neuroscience 31: 13452—13457. Doi: 10.1523/JNEUROSCI.2156-11.2011.

Singh, J., Doherty, K.A. (2020). Use of a mild-gain hearing aid by middle-age normal-hearing adults who do and do not self-report trouble hearing in background noise. American Journal of Audiology 29, 419-428. Doi: 10.1044/2020_AJA-19-00051.

Taal C.H., Hendricks R.C., Heusdens R., Jensen J. (2011) An algorithm for intelligibility prediction of time–frequency weighted noisy speech. IEEE Transactions on Audio, Speech, and Language Processing 19, 2125–2136. Doi: 10.1109/TASL.2011.2114881.

Tremblay K.L., Pinto A., Fischer M.E., Klein B.E.K., Klein R., Levy S., Tweed T.S., Cruickshanks K.J. (2015) Self-reported hearing difficulties among adults with normal audiograms: The Beaver Dam Offspring Study. Ear and Hearing 36: e290—e299. Doi: 10.1097/AUD.0000000000000195.

Valderrama J.T., Beach E.F., Yeend I., Sharma M., Van Dun B., Dillon H. (2018) Effects of lifetime noise exposure on the middle-age human auditory brainstem response, tinnitus and speech-in-noise intelligibility. Hearing Research 365: 36—48. Doi: 10.1016/j.heares.2018.06.003.

Valderrama J.T., de la Torre A., McAlpine D. (2022) The hunt for hidden hearing loss in humans: From preclinical studies to effective interventions. Frontiers in Neuroscience 16: 1000304. Doi: 10.3389/fnins.2022.1000304.

Verhulst S., Jagadeesh A., Mauermann M., Ernst F. (2016) Individual differences in auditory brainstem response wave characteristics: Relations to different aspects of peripheral hearing loss. Trends in Hearing 20: 2331216516672186. Doi: 10.1177/2331216516672186.

Weisser A., Buchholz J.M., Oreinos C., Badajoz-Davila J., Galloway J., Beechey T., Keidser G. (2019) The ambisonics recordings of typical 32nvironments (ARTE) database. Acta Acustica united with Acustica 105: 695—713. Doi: 10.3813/AAA.919349.

Wilkinson M.D., Dumontier M., Aalbersberg I.J., et al. (2016) The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3: 160018. Doi: 10.1038/sdata.2016.18.

World Health Organization (2021). World Report on Hearing. Geneva: World Health Organization. ISBN 978-92-4-002048-1 (electronic version).

Wu Y.H., Stangl E., Chipara O., Hasan S.S., Welhaven A., Oleson J. (2018) Characteristics of Real-World Signal-to-noise Ratios and Speech Listening Situations of Older Adults with Mild-to-Moderate Hearing Loss. Ear and Hearing 39, 293—304. Doi: 10.1097/AUD.0000000000000486.

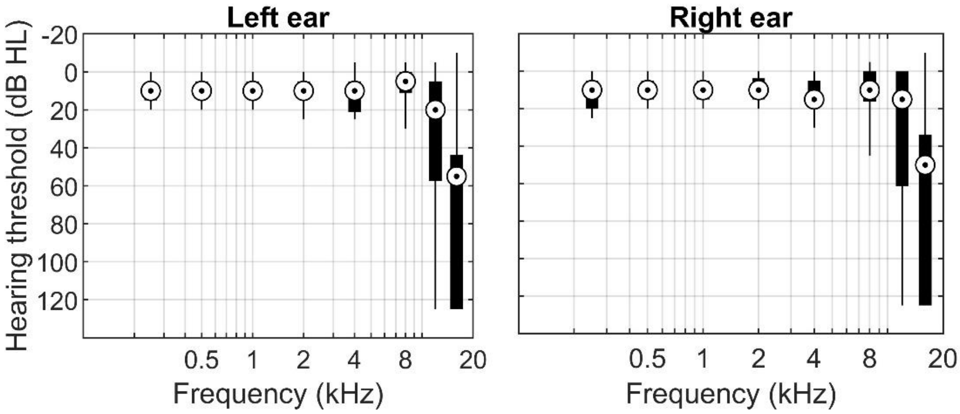
Tables

- Table 1. Speech intelligibility index—signal-to-noise ratio (SII-SNR) advantage measured at the eardrum with AirPods Pro configured in different *Conversation Boost* (CB) and *Ambient Noise Reduction* (ANR) settings relative to the unaided condition.

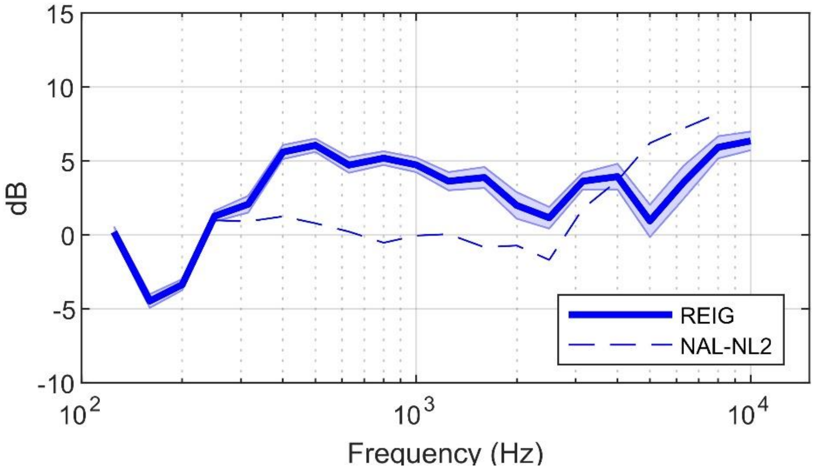
CB-ON, ANR-100%	+5.36 dB
CB-ON, ANR-0%	+3.20 dB
CB-OFF, ANR-100%	+1.85 dB

Figures

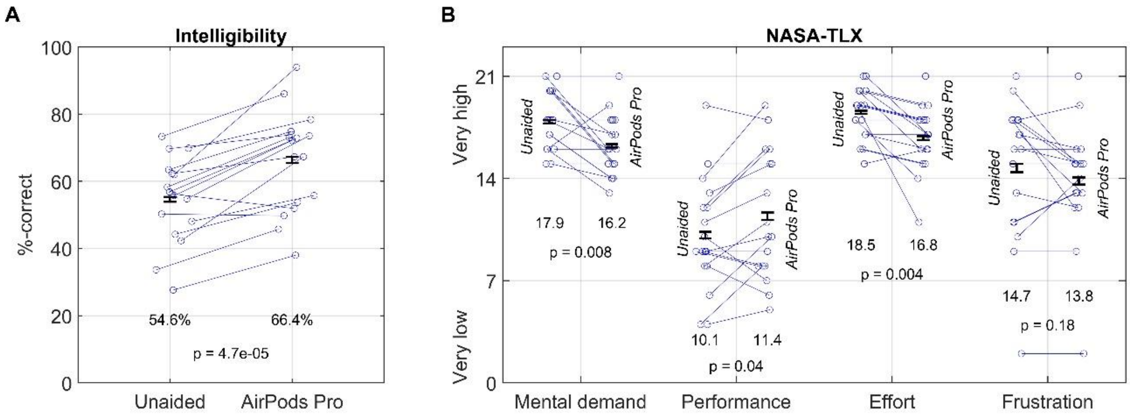
- Figure 1. Pure-tone hearing thresholds from 0.25 to 16 kHz in left and right ears—boxplots represent the quartiles of the distributions.



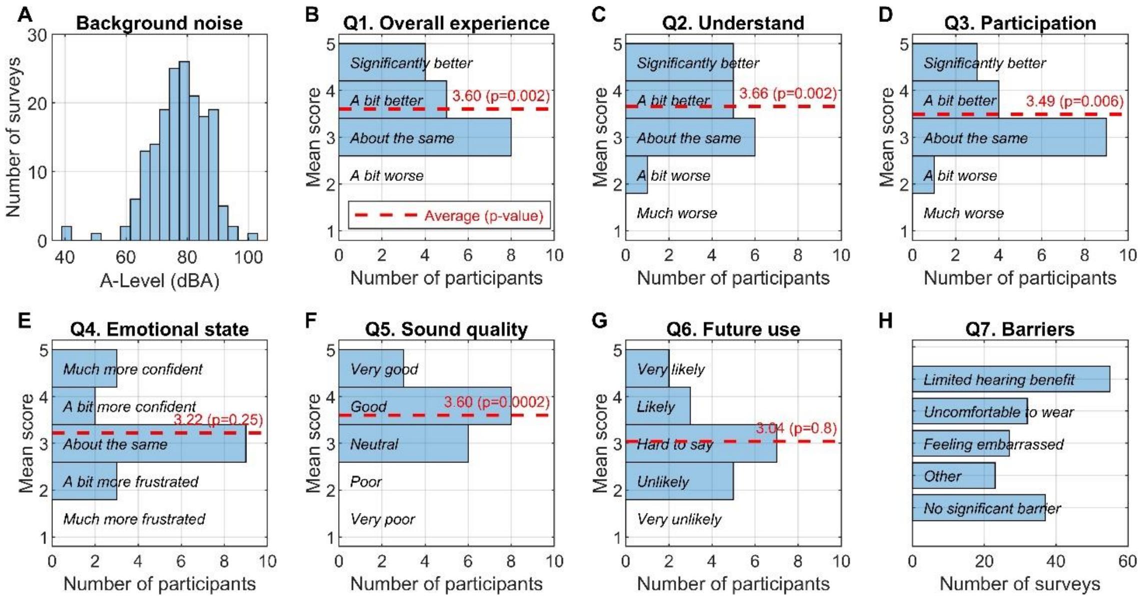
- Figure 2. Averaged Real Ear Insertion Gain (REIG) across participants when the acoustic stimulus was presented at 65 dB SPL, and *Conversation Boost* was enabled in AirPods Pro. Shaded error bars represent the standard error of the mean, and the dotted thin line represents the target amplification of a hearing aid according to NAL-NL2 prescription.



- Figure 3. [A] Intelligibility (% morphemes correct) in the BEST test with and without AirPods Pro for each participant. [B] Subjective workload associated with the BEST test determined by four questions from the NASA-TLX scale, including questions about mental demand, performance, effort and frustration. In the two panels, error bars represent the standard error of the mean. The mean score per condition and the *p*-value resulting from paired *t*-test analyses are shown below the data.



- Figure 4. Real-world NEMA surveys. [A] Histogram of the A-weighted background noise level. [B-G] Histogram of the mean score per participant to questions 1 to 6 (Q1 – Q6) about their overall hearing experience, speech-in-noise understanding, participation in conversations, emotional state, sound quality of the AirPods Pro, and future use. The dotted horizontal line presents the average score across participants—its numeric value and the *p*-value resulting from a one-group t-test vs a score of 3 (neutrality) are above this line. [H] Frequency occurrence of different barriers.



- Figure 5. Histogram of the SADL Global score. The dotted horizontal line presents the average score across participants. The 20th and 80th percentile of the SADL Global score reported by 365 hearing aid users is presented next to the histogram (Cox and Alexander, 1999).