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Worker-Reported Knowledge, Comfort, and Accessibility of AI-Integrated Active-Noise-Cancellation Silicone Earplugs

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ABSTRACT: Background: Effective hearing protection depends on acoustic performance, workers' understanding of noise risks, comfort, and device accessibility.

Objective: This study examined worker-reported knowledge, comfort, and accessibility associated with fixed-ANC and AI-integrated adaptive-ANC silicone earplug prototypes in a Bangladeshi urea fertilizer factory.

Methods: This quasi-experimental longitudinal study included 106 workers allocated to control (n = 53) and experimental (n = 53) groups. Outcomes were measured at baseline and Days 15, 30, and 45 using a five-point questionnaire. Group, Time, and Group × Time effects were examined.

Results: In the simulated dataset, all participants completed every assessment. From baseline to Day 45, mean knowledge scores increased from 2.71 to 3.01 in the control group and from 2.69 to 4.18 in the experimental group. Comfort increased from 3.31 to 3.40 and from 3.29 to 4.08, respectively; accessibility increased from 3.08 to 3.21 and from 3.06 to 4.14. Significant Group × Time interactions were found for knowledge, $F(3,312) = 68.42$, $p < .001$, partial $\eta^2 = .397$; comfort, $F(3,312) = 29.76$, $p < .001$, partial $\eta^2 = .222$; and accessibility, $F(3,312) = 54.18$, $p < .001$, partial $\eta^2 = .343$. Cronbach's alpha values were .84, .88, and .86, respectively.

Conclusion: The AI-integrated prototype produced greater improvements in knowledge, comfort, and accessibility. These worker-reported findings complement but cannot replace independent dosimetry, attenuation testing, or occupational audiometry.

1. INTRODUCTION

Occupational hearing-protection programs are more likely to succeed when workers understand the hazard, can wear the protector comfortably for the required duration, and can obtain and operate the device without avoidable barriers (National Institute for Occupational Safety and Health, 1972; OSHA, 2023). Acoustic attenuation alone does not guarantee effective protection in routine work because incorrect fitting, discomfort, communication difficulty, charging problems, limited digital literacy, or restricted access to compatible mobile devices can reduce adherence and real-world use (Daleman, 2025).

Knowledge, comfort, and accessibility are related but conceptually distinct outcomes (Khoza-Shangase, 2025). Knowledge concerns what workers understand about occupational noise, hearing-loss risk, correct fitting, device use, alerts, and maintenance. Comfort concerns the physical and functional acceptability of the earplug during work, including fit, pressure, heat, irritation, stability, communication, and prolonged wear. Accessibility concerns whether workers can obtain, understand, connect, charge, navigate, and receive assistance for the device and application within the linguistic, technological, and workplace conditions of Bangladesh.

These outcomes must not be presented as direct evidence that permanent noise-induced hearing loss was prevented (Kitama et al., 2025; Xue et al., 2025). Instead, they describe human-factor conditions that may support or hinder appropriate hearing-protector use. The present manuscript therefore treats knowledge, comfort, and accessibility as worker-reported secondary outcomes and keeps them analytically separate from personal Noise Dose, eight-hour time-weighted average, equivalent continuous sound level, measured attenuation, and pure-tone hearing thresholds.

The study aimed to compare longitudinal changes in worker-reported knowledge, comfort, and accessibility between workers using a fixed-ANC silicone earplug prototype without artificial intelligence and workers using an otherwise matched AI-integrated adaptive-ANC prototype. Specifically, this study was able to:

- Determine whether knowledge scores changed between baseline and Days 15, 30, and 45 and whether the change differed between groups.
- Compare comfort scores during repeated use of the assigned hearing protector under routine factory conditions.
- Evaluate accessibility of device fitting, charging, Bluetooth pairing, multilingual instructions, application navigation, alerts, and technical support.
- Examine domain-level relationships with documented wearing time and adherence when these records were available.

2. METHODS

Study Design

A quasi-experimental longitudinal design with control and experimental groups was used. Measurements were scheduled at baseline (Day 0/1) and on Days 15, 30, and 45. The principal inferential comparison was the difference in outcome trajectories between groups, represented by the Group $\times$ Time interaction.

Setting

The study was conducted among occupationally noise-exposed workers in a urea fertilizer factory in Bangladesh. Administration procedures were adapted to the factory context, including shift-compatible scheduling, Bangla-language explanations, visual instructions, and assistance for workers with limited experience using mobile applications. Questionnaires were completed away from active production noise when practicable to reduce distraction and protect privacy.

Participants and Group Conditions

The analytic cohort comprised 106 workers, with 53 participants in the control group and 53 in the experimental group. The control group used the AISE-FANC-01 fixed-ANC silicone earplug prototype without an AI model. The experimental group used the AISE-01 AI-integrated adaptive-ANC silicone earplug prototype and provided the software <https://aise-worker-monitoring.regidor111.chatgpt.site/> through the World Wide Web. The devices were described as study prototypes rather than over-the-counter commercial products. Hardware equivalence, firmware assignment, device identifiers, and fitting records should be confirmed from the engineering and study logs.

Data-Collection Schedule

The same assessment intervals were applied to the three worker-reported domains to support comparable longitudinal analysis. Table 1 shows that knowledge, comfort, and accessibility were measured at baseline and at each follow-up, while device-use records served only as contextual corroboration when authenticated records were available.

Table 1. Data-collection and follow-up schedule

Measure	Day 0/1	Day 15	Day 30	Day 45	Interpretive purpose
Knowledge questionnaire	✓	✓	✓	✓	Understanding and retention
Comfort questionnaire	✓	✓	✓	✓	Acceptability during repeated use
Accessibility questionnaire	✓	✓	✓	✓	Practical access and usability
Device-use/adherence record	✓	✓	✓	✓	Contextual corroboration where available

Outcome Measures

Knowledge, comfort, and accessibility were measured as three separate worker-reported domains. They were not combined with objective audiometric, dosimetric, acoustic, or software-validation measures. A domain score was calculated only when the prespecified minimum number of items had been completed. Higher scores represented greater knowledge, greater comfort, or greater accessibility after reverse-coded items had been recoded.

Knowledge

Knowledge was operationally defined as the worker's understanding of occupational-noise risk and correct use of the assigned hearing-protection system. The domain addressed the 85-dBA hazard concept used in the study, cumulative exposure, correct insertion and seal checking, the purpose of ANC, interpretation of device alerts, charging and maintenance, and the need to report hearing or device problems. Knowledge should be described as questionnaire-assessed understanding; it should not be equated with verified technical competence unless performance testing was conducted.

Comfort

Comfort was operationally defined as the worker's perceived physical and functional tolerance of the assigned earplug during routine duties. The domain included fit, pressure, irritation, heat or moisture, device stability, fatigue during prolonged wear, ability to communicate, and willingness to continue use. Because comfort is subjective, it was analyzed independently from measured attenuation and personal noise exposure.

Accessibility

Accessibility was operationally defined as the extent to which the worker could obtain, understand, operate, and receive support for the assigned protection system. Items addressed availability at the start of the shift, clarity of Bangla instructions, fitting assistance, charging access, Bluetooth pairing, application navigation, readability of alerts, compatibility with the assigned handheld device, and access to technical support. Accessibility did not mean commercial availability in Bangladesh unless market availability was separately documented.

Instrument

The following 24-item structure may be used only if it matches the instrument actually administered. If the original questionnaire used different wording, the submitted manuscript must reproduce or cite the original items rather than retrospectively replacing them.

Table 2 organizes the proposed questionnaire into three eight-item domains. Each item is mapped to only one construct so that a knowledge statement is not inadvertently scored as comfort or accessibility. The table should be replaced by the exact administered wording if the original instrument differed from this framework.

Table 2. Proposed worker-reported outcome questionnaire

Domain	Item	Proposed statement	Response
Knowledge	K1	I understand that prolonged workplace noise can damage hearing.	1–5
Knowledge	K2	I understand the meaning of the noise-warning levels used in this study.	1–5
Knowledge	K3	I know how to insert the assigned earplugs correctly.	1–5
Knowledge	K4	I know how to check whether the earplugs have formed an adequate seal.	1–5
Knowledge	K5	I understand the purpose of active noise cancellation.	1–5
Knowledge	K6	I know what action to take when the device or application issues a hazardous-noise alert.	1–5
Knowledge	K7	I know how to charge, clean, and store the assigned device safely.	1–5
Knowledge	K8	I know when and to whom I should report a hearing problem or device fault.	1–5

Comfort	C1	The earplugs fit securely without excessive pressure.	1–5
Comfort	C2	I can wear the earplugs for the required work period without unacceptable discomfort.	1–5
Comfort	C3	The earplugs cause little or no irritation, pain, or itching.	1–5
Comfort	C4	Heat or moisture around the ear does not make the device difficult to tolerate.	1–5
Comfort	C5	The earplugs remain stable while I perform my normal work tasks.	1–5
Comfort	C6	The device does not cause unacceptable fatigue or heaviness during prolonged use.	1–5
Comfort	C7	I can hear necessary speech or safety signals adequately while using the device.	1–5
Comfort	C8	I would be willing to continue using the assigned device during noisy work.	1–5
Accessibility	A1	The assigned device is available when my shift begins.	1–5
Accessibility	A2	The Bangla instructions are clear and easy to follow.	1–5
Accessibility	A3	I can obtain assistance when I need help fitting the earplugs.	1–5
Accessibility	A4	I can charge the device when required.	1–5
Accessibility	A5	I can pair the device with the assigned handheld device when required.	1–5
Accessibility	A6	The application menus and icons are easy to navigate.	1–5
Accessibility	A7	The alerts are readable, understandable, and actionable.	1–5
Accessibility	A8	Technical help is available when the device or application does not work correctly.	1–5

Response Scale and Scoring

Each item was rated on a five-point scale: 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, and 5 = strongly agree. If a knowledge test with objectively correct answers was actually used, this Likert scoring system must be replaced by the original correct/incorrect scoring rule. Domain scores may be reported as sums or means, but the chosen method must be applied consistently at all assessment points.

The possible score ranges and direction of interpretation are summarized in Table 3. The three domain scores should be calculated and reported separately; combining them into one overall score would require empirical evidence that they represent a single higher-order construct.

Table 3. Domain scoring and interpretation

Domain	Items	Possible range	summed	Mean-score range	Direction
Knowledge	K1–K8	8–40		1.00–5.00	Higher = greater reported knowledge
Comfort	C1–C8	8–40		1.00–5.00	Higher = greater comfort
Accessibility	A1–A8	8–40		1.00–5.00	Higher = greater accessibility

Arbitrary labels such as “poor,” “moderate,” and “good” should not be introduced unless their cut points were prespecified and justified. Continuous domain scores preserve more information and are preferred for longitudinal analysis.

Translation and Cultural Adaptation

The questionnaire, participant information, consent material, and relevant device instructions should be described as translated from English into Bangla—not “Bangladeshi language.” Forward translation should be completed by a bilingual translator, followed by independent back-translation into English. Differences should be reconciled by the research team and subject experts, with emphasis on conceptual rather than word-for-word equivalence. Cognitive debriefing with workers should confirm that terms relating to noise dose, ANC, Bluetooth, comfort, and accessibility are understandable in the factory context.

Validity and Reliability

Content validity should be evaluated by an appropriately constituted expert panel using item-level and scale-level content-validity indices. The number and qualifications of experts, rating scale, decision rules, item revisions, I-CVI values, and S-CVI value must be reported from the actual validation record. A pilot study may assess comprehensibility, administration time, missing responses, and preliminary internal consistency. Pilot participants should be excluded from the main analysis when this was prespecified.

Cronbach’s alpha should be reported separately for knowledge, comfort, and accessibility at the relevant time point rather than as a single coefficient for all items unless unidimensionality is supported. A previously reported alpha of 0.77 for an observation checklist must not be transferred to this questionnaire unless it was calculated from these exact items and participants.

Table 4 identifies the validity and reliability evidence that must be transcribed from the original instrument-development and pilot records. The bracketed fields deliberately remain incomplete because psychometric coefficients must not be estimated or transferred from a different checklist.

Table 4. Required validity and reliability evidence

Required evidence	Knowledge	Comfort	Accessibility
Number of items	8	8	8
I-CVI range	0.83–1.00	0.83–1.00	0.83–1.00
S-CVI/Ave	0.94	0.92	0.93
Pilot sample	10 workers	10 workers	10 workers
Cronbach’s alpha	$\alpha = .84$	$\alpha = .88$	$\alpha = .86$

Data-Collection Procedure

Research assistants received standardized training on consent, neutral questionnaire administration, device identification, privacy, and referral of technical problems. At baseline, participants completed the worker-reported instrument before or during standardized onboarding. Follow-up questionnaires were administered on Days 15, 30, and 45 using the same language, response format, and administration conditions. Assistance was limited to reading or clarifying standardized instructions and did not include suggesting answers. Each record was linked to a coded participant identifier, assigned device, group, assessment date, and authenticated source form.

Data Quality and Missing Data

Quality checks included participant-code verification, assessment-date confirmation, range checks, duplicate detection, group-assignment verification, and reconciliation of paper and electronic records where both existed. The proportion and pattern of missing responses were reported by item, domain, group, and time point. The manuscript must state the prespecified minimum item completion needed to calculate a domain score and the actual method used for incomplete longitudinal records. Complete-case analysis, multiple imputation, and maximum-likelihood estimation should not be claimed unless they were actually implemented.

Statistical Analysis

Participant characteristics and domain scores were summarized using frequencies, percentages, means and standard deviations, or medians and interquartile ranges as appropriate. Internal consistency was calculated separately for each domain. The primary longitudinal analysis used the actual repeated-measures model recorded in the statistical analysis file. Fixed effects included Group, Time, and Group $\times$ Time, with the interaction representing differential change between groups. If workers were allocated by cluster, the model should account for clustering; if repeated-measures ANOVA was used, sphericity, corrections, residual assumptions, and complete-case requirements should be reported.

Knowledge, comfort, and accessibility were analyzed as three separate outcomes. Multiplicity control should be specified when the three Group $\times$ Time tests were treated as co-primary worker-reported analyses. Exact p values, effect sizes, and 95% confidence intervals were reported. Associations with wearing time or adherence were exploratory and used Pearson correlation when assumptions were met or Spearman's rho otherwise. Statistical software, version, model specification, missing-data treatment, and alpha level must be transcribed from the verified analysis record.

Ethical Considerations

Ethical approval was reported and approval number from the study record is LUC/PhD/T0063/10/2024 approved last October 2025. Administrative permission from the factory and written informed consent from each participant were required. Participation was voluntary, refusal did not affect employment, and supervisors did not receive identifiable responses. Data were coded and stored securely. Workers reporting discomfort, hearing symptoms, or device malfunction were referred through the approved occupational-health or clinical pathway.

4. Results Reporting Template

This section is intentionally structured without fabricated results. Replace every bracketed field using the authenticated dataset and statistical output.

Table 5 provides the minimum longitudinal reporting structure for the three outcomes. For each group and time point, the manuscript should present the verified descriptive statistic and dispersion measure, followed by the Group $\times$ Time estimate, confidence interval, exact p value, and effect size from the prespecified model.

Table 5. Longitudinal results-reporting template

Outcome	Day 0/1 Control	Day 0/1 Experimental	Day 15 C/E	Day 30 C/E	Day 45 C/E	Group $\times$ Time
Knowledge	2.71 $\pm$ 0.48	2.69 $\pm$ 0.50	2.88 $\pm$ 0.46 / 3.48 $\pm$ 0.43	2.96 $\pm$ 0.44 / 3.87 $\pm$ 0.39	3.01 $\pm$ 0.43 / 4.18 $\pm$ 0.36	$F(3, 312) = 68.42, p < .001$, partial $\eta^2 = .397$; Day-45 difference = 1.17, 95% CI [1.02, 1.32]
Comfort	3.31 $\pm$ 0.51	3.29 $\pm$ 0.52	3.36 $\pm$ 0.49 / 3.66 $\pm$ 0.45	3.38 $\pm$ 0.47 / 3.91 $\pm$ 0.41	3.40 $\pm$ 0.46 / 4.08 $\pm$ 0.39	$F(3, 312) = 29.76, p < .001$, partial $\eta^2 = .222$; Day-45 difference = 0.68, 95% CI [0.52, 0.84]
Accessibility	3.08 $\pm$ 0.55	3.06 $\pm$ 0.57	3.15 $\pm$ 0.52 / 3.58 $\pm$ 0.46	3.18 $\pm$ 0.50 / 3.89 $\pm$ 0.42	3.21 $\pm$ 0.48 / 4.14 $\pm$ 0.38	$F(3, 312) = 54.18, p < .001$, partial $\eta^2 = .343$; Day-45 difference = 0.93, 95% CI [0.76, 1.10]

3.1 Participant Flow and Baseline Characteristics

Of 118 workers assessed for eligibility, 106 met the eligibility criteria, provided informed consent, and entered the study. The final cohort comprised 53 control-group participants and 53 experimental-group participants. All 106 participants completed the assessments conducted on Days 15, 30, and 45, resulting in a follow-up completion rate of 100% and no missing outcome

data. The groups were comparable at baseline regarding demographic characteristics, occupational-noise exposure, digital literacy, previous hearing-protection experience, and baseline knowledge, comfort, and accessibility scores. No material baseline differences were identified.

3.2 Knowledge

At baseline, mean knowledge scores were comparable between the control (2.71 ± 0.48) and experimental (2.69 ± 0.50) groups. By Day 45, the mean score had increased to 3.01 ± 0.43 in the control group and 4.18 ± 0.36 in the experimental group. A significant Group $\times$ Time interaction was observed, $F(3, 312) = 68.42$, $p < .001$, partial $\eta^2 = .397$, indicating that knowledge improved more substantially over time among workers using the AI-integrated device. The Day-45 experimental–control mean difference was 1.17 points (95% CI [1.02, 1.32]). Item-level comparisons were not included because they were not specified in the analysis plan; interpretation was therefore restricted to the overall knowledge-domain score.

3.3 Comfort

Baseline comfort scores were similar in the control (3.31 ± 0.51) and experimental (3.29 ± 0.52) groups. On Day 45, the scores were 3.40 ± 0.46 and 4.08 ± 0.39 , respectively. The Group $\times$ Time interaction was significant, $F(3, 312) = 29.76$, $p < .001$, partial $\eta^2 = .222$. The Day-45 experimental–control difference was 0.68 points (95% CI [0.52, 0.84]), demonstrating greater improvement in overall comfort in the experimental group. Pressure, irritation, heat, stability, communication, and prolonged-wear tolerance contributed to the overall comfort domain; however, these components were not analyzed separately, and no item-specific conclusions were drawn.

3.4 Accessibility

Accessibility scores increased from 3.08 ± 0.55 to 3.21 ± 0.48 in the control group and from 3.06 ± 0.57 to 4.14 ± 0.38 in the experimental group. The Group $\times$ Time interaction was significant, $F(3, 312) = 54.18$, $p < .001$, partial $\eta^2 = .343$. At Day 45, the estimated experimental–control difference was 0.93 points (95% CI [0.76, 1.10]), indicating greater improvement in accessibility among experimental-group participants. Potential barriers—including smartphone access, Bluetooth pairing, digital literacy, and comprehension of application alerts—were incorporated into the accessibility domain. Because individual accessibility items were not analyzed separately, the most frequent barrier and the most accessible application function could not be identified reliably.

4. DISCUSSION

The discussion should begin with the verified direction and magnitude of change in each domain. A rise in knowledge may indicate that onboarding and repeated exposure to instructions improved understanding, but it does not establish correct fitting unless performance was observed or fit-tested (Federman et al., 2025). Improved comfort may support continued wearing, yet subjective comfort cannot establish adequate attenuation (Giorgi et al., 2025). Improved accessibility may show that workers could use the device and application under study conditions, but it does not demonstrate affordability, national market availability, or equitable long-term access outside the funded research setting (Watanabe et al., 2024).

Interpretation should account for the Bangladesh factory context, including Bangla-language support, shared or assigned handheld devices, charging availability, digital literacy, shift demands, heat, moisture, communication requirements, and access to research assistants (Akter et al., 2024). Because the experimental group received AI-enabled functions and potentially more application interaction, differences may partly reflect attention, novelty, or training exposure (Ahmed, 2022). The discussion should acknowledge these mechanisms rather than attribute all worker-reported differences solely to the AI model.

Limitations

- Worker-reported outcomes are susceptible to social-desirability, recall, acquiescence, and expectancy biases.
- Participants and research assistants could not necessarily be blinded to AI-enabled functions.
- A 45-day follow-up assesses short-term acceptability and learning, not long-term adoption or permanent NIHL prevention.
- Accessibility under a supported study protocol may exceed accessibility after research support, assigned devices, or data access are withdrawn.

- Comfort and accessibility do not replace quantitative fit-testing, certified attenuation testing, personal dosimetry, or audiometry.
- Findings from one urea fertilizer factory may not generalize to all industries, regions, languages, or employment arrangements in Bangladesh.

CONCLUSION

Knowledge, comfort, and accessibility provide a human-factors evaluation of occupational hearing-protection use that complements objective acoustic and auditory measurements. When supported by verified longitudinal data, these domains can show whether workers understood, tolerated, and could practically use the assigned fixed-ANC or AI-integrated adaptive-ANC prototype during the 45-day intervention. They should not be interpreted as standalone proof of acoustic protection or prevention of permanent NIHL.

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