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Emotional Prosody Evaluation in Adults with Cochlear Implants

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Highlights

What are the main findings?

- Adults with unilateral and bilateral cochlear implants showed substantially poorer recognition of vocal emotions than typical-hearing participants, across nearly all tested emotions.
- No consistent statistically significant advantage of bilateral over unilateral implantation was detected for emotional prosody recognition; older age and lower education were associated with poorer performance.

What are the implications of the main findings?

- Adults with cochlear implants showed markedly poorer vocal emotion recognition than typical-hearing participants, although the present study did not directly assess the acoustic mechanisms underlying this deficit.
- Clinical rehabilitation should extend beyond speech intelligibility to include emotion perception and audiovisual training, while future technological development should investigate approaches aimed at improving access to acoustic information relevant to emotional prosody.

Abstract

Objectives: This cross-sectional study evaluates emotional prosody recognition in adults with unilateral cochlear implants (UCI, n = 22), bilateral cochlear implants (BCI, n = 15), and typical hearing, defined as normal hearing sensitivity confirmed by standard audiometric assessment (TH, n = 21), using the Montreal Affective Voices (MAV). Secondary aims assess demographic and clinical factors influencing performance. **Materials and Methods**: Participants underwent audiological testing (PTA5, speech-in-noise at SNR +5 dB), cognitive screening (MoCA), visual emotion recognition, and MAV assessment for emotion identification (happiness, sadness, fear, anger, surprise, pleasure, pain, disgust, neutral), and subjective valence ratings. Mean age ± SD was 56.2 ± 8.1 years in UCI participants, 46.1 ± 19.7 years in BCI participants, and 35.5 ± 11.5 years in TH participants. Group comparisons were performed using non-parametric tests (Kruskal–Wallis, Mann–Whitney U), and multivariable linear regression models adjusted for study group, age, and education, with corresponding visual emotion-recognition scores and speech-in-noise performance at +5 dB SNR evaluated as additional covariates. **Results**: Both CI groups showed profound deficits in auditory emotion recognition (unadjusted total scores: UCI 30.4 ± 10.6, BCI 30.1 ± 8.7 vs. TH 61.9 ± 7.4; $p < 0.001$). After FDR correction, significant overall group

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effects were observed for eight of the nine emotion-specific outcomes; Sadness did not remain significant after correction. No Bonferroni-adjusted UCI-versus-BCI comparison was significant. Older age and lower education level were associated with poorer performance for selected outcomes. Visual emotion-recognition scores were positively associated with auditory performance for Anger and Neutral. Global cognition and disability (WHODAS 2.0) were comparable across groups. **Conclusions**: Cochlear implant users showed substantially poorer recognition of emotional prosody than typical-hearing participants, with no consistent statistically significant difference between unilateral and bilateral users. Technological improvements and targeted rehabilitation may help to enhance socioemotional communication in CI users.

Keywords: cochlear implants; emotional prosody; Montreal affective voices; auditory emotion recognition

1. Introduction

Emotional or affective prosody refers to the nonverbal components of language that facilitate the recognition of emotions during interpersonal communication. Key modalities, such as facial mimicry, proxemics, and kinesics, work synergistically to convey nonverbal information, enabling individuals to infer the emotions, mental states, and potential actions of their conversational partners [1,2]. In conversational contexts, interlocutors predominantly rely on prosody and facial expressions to rapidly and accurately infer emotional cues, with emotional prosody becoming particularly salient when facial expressions are ambiguous [3]. The integration of visual and auditory cues is critical for effective emotional processing; thus, sensory impairments can disrupt this integration, leading to challenges in accurately evaluating emotions during social interactions [4]. Emotional prosody is expressed through variations in frequency, intensity, timbre, articulatory speed, and pauses in speech [5–7]. This prosodic information operates independently of semantic content and interacts with verbal communication, as seen in sarcasm. In most studies on emotional and prosodic processing, experimental materials consist of sentences, words, or connected speech, such that emotional and prosodic processing is inherently influenced by the accompanying semantic content [8]. Individuals with severe-to-profound sensorineural hearing loss (SNHL) or those using cochlear implants (CIs) frequently encounter difficulties perceiving and expressing emotional prosody [9,10]. Although CIs are designed to restore some auditory function, they often lack sufficient frequency resolution, which is essential for the accurate discrimination of frequency patterns necessary for emotion recognition. This limitation can adversely affect social interactions and the overall quality of life of CI users [11,12]. The fidelity of voice pitch representation in CIs is often inadequate, leading to difficulties in speech perception that relies on pitch, such as prosody and lexical tones [13,14]. Such perceptual deficits are believed to contribute to the challenges faced by CI users in identifying emotional prosody [15,16]. Furthermore, analogous difficulties have been observed in normally hearing individuals exposed to CI-simulated speech, underscoring the inadequacy of secondary cues in achieving normative levels of vocal emotion identification [15,17,18]. Therefore, addressing these perceptual deficits is critical for enhancing the emotional communication capabilities of cochlear implants.

The impact of SNHL and CIs on emotional prosody in the adult population has shown mixed results; this variability underscores the need for studies that employ standardized tools to provide more consistent insights into emotional prosody recognition in CI users.

The primary aim of the study was therefore to examine emotional prosody recognition in adults with unilateral cochlear implants (UCIs), bilateral cochlear implants (BCIs), and

typical hearing (TH), with particular attention to whether bilateral implantation is associated with better performance than unilateral implantation using the Montreal Affective Voices (MAV) [19]; we hypothesized that both CI groups would show poorer emotional prosody recognition than TH participants and explored whether bilateral auditory input would confer an advantage over unilateral implantation. This direct UCI–BCI comparison was considered clinically relevant because bilateral severe-to-profound hearing loss may be managed with either unilateral or bilateral implantation, leaving different degrees of access to binaural auditory information. Secondary objectives were to evaluate the contribution of demographic and clinical factors potentially affecting emotional prosody perception in CI users, including age, sex, speech discrimination in quiet and noisy conditions, and time of device use.

2. Materials and Methods

2.1. Ethical Consideration

All procedures contributing to this work were conducted in accordance with the ethical standards of the relevant national and institutional guidelines on human experimentation and with the principles outlined in the Declaration of Helsinki (revised in 2024). Ethical approval was granted by the local Institutional Review Board (approval number 7207/2023CE 22/05/2023). Written informed consent was obtained from all participants before any study-related procedure. This research received no specific funding from any funding agency, commercial organization, or not-for-profit sector.

2.2. Study Design

This study adopted a cross-sectional comparative design to investigate emotional prosody recognition in adult cochlear implant users and typical-hearing controls, and to explore differences between unilateral and bilateral cochlear implant configurations. Participants were classified into three groups based on hearing status and device configuration: unilateral cochlear implant (UCI) users, bilateral cochlear implant (BCI) users, and typical-hearing (TH) controls. Between-group comparisons were performed for auditory emotion recognition performance, while the influence of demographic, audiological, and clinical factors was explored within the cochlear implant cohort. This cross-sectional comparison was not designed to isolate the effect of cochlear implantation from the effect of the underlying hearing loss or from other forms of auditory rehabilitation.

2.3. Participants and Eligibility Criteria

The following general eligibility criteria were applied to all participants, irrespective of group assignment. Additional group-specific criteria were applied to cochlear implant users and typical-hearing participants, as detailed below.

General inclusion criteria:

- Age ≥ 18 years;
- Ability to personally decide on study participation;
- Italian as the primary language.

General exclusion criteria:

- Moderate-to-severe cognitive impairment or psychosis;
- Significant dependency or frailty;
- Inability to complete self-assessment questionnaires independently;
- Significant comorbidities preventing study participation (e.g., blindness, severe mobility impairment, severe aphasia, and others);
- Medical conditions that could interfere with the study procedures.

Cochlear implant groups:

Adults with severe-to-profound sensorineural hearing loss (SNHL) using cochlear implants were consecutively recruited among eligible patients attending the study center.

The difference in group size between UCI and BCI participants reflected the availability of eligible patients during recruitment, with fewer bilateral CI users available for inclusion.

Typical-hearing participants were recruited separately from available individuals meeting the eligibility criteria, without consecutive sampling. Because group membership was evident from participants' hearing status and device configuration, examiners were not blinded to group assignment during test administration and scoring.

Before implantation, all CI participants had bilateral severe-to-profound sensorineural hearing loss and insufficient benefit from conventional hearing aids, consistent with the clinical indication for cochlear implantation.

The indication for cochlear implantation was based on established Italian clinical criteria for adult CI candidacy, primarily bilateral severe-to-profound sensorineural hearing loss with insufficient benefit from conventional hearing aids [20].

Additional inclusion criteria for the CI groups were:

- Use of a unilateral or bilateral perimodiolar CI (Cochlear Ltd., Sydney, Australia) for at least six months and for more than 10 h per day;
- Use of an Advanced Combination Encoder (ACE)-based strategy with all electrodes active.

Additional exclusion criteria for the CI groups were:

- Unilateral hearing loss;
- Retrocochlear hearing loss or central auditory impairment.

Additional clinical information regarding cochlear implantation, including the indication for implantation, preoperative hearing status, age at onset of deafness, prelingual versus postlingual deafness, age at implantation, and etiology of hearing loss, was retrieved from the clinical records for the characterization of the CI cohort. History of meningitis was also specifically reviewed.

Typical-hearing group:

The typical-hearing (TH) group includes adults with no history of hearing impairment.

All TH participants showed normal hearing sensitivity, as confirmed by standard audiometric assessment, and met the same general eligibility criteria for age, language proficiency, and cognitive status.

2.4. Procedures

2.4.1. Audiological Assessment

Audiological evaluation included pure-tone audiometry and speech recognition testing under free-field conditions. Testing was conducted using a Madsen Astera2 audiometer (GN Otometrics, Taastrup, Denmark) in a sound-attenuating booth, in accordance with IEC 60645-1 and ISO 389-1 standards. The pure-tone average at 250, 500, 1000, 2000, and 4000 Hz (PTA5) was used to characterize hearing sensitivity, as it provides a broader representation of the speech frequency range compared to PTA4. Frequencies at 6 and 8 kHz were not included in the PTA calculation because the purpose of this measure was to summarize hearing sensitivity across the frequency range most relevant to speech perception rather than to characterize extended high-frequency hearing.

Speech recognition in quiet conditions was evaluated in a sound field using three 20-word lists of Italian phonemically balanced disyllabic words from the speech material developed by Turrini et al. [21] administered at 65 dB SPL and 0° azimuth. The scores were reported as the percentage of correctly repeated words.

Speech recognition in noisy conditions was measured in a sound field using the cochlear implant configuration adopted for the study assessments. Tests were conducted in a sound-treated chamber using a loudspeaker positioned one meter away from the subject's head (S0N0). The stimuli consisted of taped disyllabic words presented at 65 dB SPL with a signal-to-noise ratio (SNR) of +10, +5, and 0 dB, using cocktail-party noise.

For UCI participants using a contralateral hearing aid in everyday life, testing was performed with the cochlear implant only, without the contralateral hearing aid, and the contralateral non-implanted ear was occluded during testing. For BCI participants, testing was performed with both cochlear implant processors active.

2.4.2. Educational Level Assessment

Participants' education level was measured by the number of years legally required to attain the education level they declared. In the Italian formal education system, compulsory education lasts eight years; 13 years are needed to obtain a high school diploma, and 18 years to obtain a college degree. Some special schools (technical or trade degree courses) may require intermediate lengths of time for completion.

2.4.3. Cognitive Assessment

Global cognitive functioning was screened using the Montreal Cognitive Assessment [22]. The MoCA assesses multiple domains, including memory, executive functioning, attention, language, visuospatial, and orientation. The subtests include tasks such as trail-making, cube and clock drawing, animal naming, digit span, serial 7 s, phonemic fluency, sentence repetition, abstraction similarities, five-word immediate and delayed recall, and orientation questions. The total score ranges from 0 to 30, with higher scores reflecting better performance; a cut-off score of <26 is commonly used to indicate possible cognitive impairment, and one extra point is added for individuals with ≤ 12 years of formal education to account for the educational effects on performance. The MoCA was selected as a brief screening instrument because it provides a multidomain assessment of global cognitive functioning within a relatively short administration time. In the present study, it was used to screen for significant cognitive impairment and to characterize baseline cognitive status across groups. In CI participants, the MoCA was administered orally in the best-aided listening condition, with written and visual support provided to facilitate access to the test instructions and items.

2.5. Auditory Emotional Prosody

To evaluate the ability to recognize emotional prosody, the Montreal Affective Voices (MAV) [19] was used: a test consisting of 90 nonverbal vocalizations comprising nine emotion categories—happiness, sadness, fear, anger, surprise, disgust, pleasure, pain, and neutral—with 10 stimuli for each category. For each vocalization, participants were asked to provide subjective ratings of affective valence, excitement/arousal, and emotional intensity. For the present analysis, only the subjective valence ratings and emotion-recognition scores were evaluated; excitement/arousal and emotional-intensity ratings were not included in the analyses reported here. Subjective valence was quantified on a 10-point scale ranging from 0, indicating extremely negative perceived affect, to 10, indicating extremely positive perceived affect. To simplify the analysis, participants were asked to identify the prevailing emotion perceived in each sound across the nine target categories. Emotion-recognition scores were calculated as the number of correctly identified stimuli, with a maximum score of 10 for each category and 90 for the total score. For the MAV, the stimuli were presented at 65 dB SPL through a loudspeaker at a 0° angle to the patient, who was positioned one meter away. The test began with a training session. During the training session, feedback

on the correct response was provided after each trial; no feedback was provided during the test blocks. The stimuli were presented in a pseudo-randomized order and divided into two blocks of 45 sounds, with an interval of approximately 30 min between the two blocks. Data were collected using a form given to the patients, who circled the emotions they recognized and indicated the degree to which they could hear them.

2.6. Visual Emotion Recognition Abilities

Visual emotion recognition abilities were assessed using a 55-item facial emotion recognition task. The task included seven emotional categories: happiness, sadness, disgust, fear, surprise, anger, and neutral expressions. Participants were required to identify the emotion represented by each facial stimulus. The total visual emotion recognition score ranged from 0 to 55 and corresponded to the total number of correctly identified expressions. Emotion-specific scores were also calculated according to the number of correctly identified stimuli within each emotional category. Reaction times were recorded for the overall task and for each emotion category. The visual task was analyzed as a study-specific secondary behavioral measure; the 55-item task used here should not be considered equivalent to the original 19-item Facial Emotion Identification Test described by Kerr and Neale [23].

2.7. Questionnaires

The Speech, Spatial, and Qualities of Hearing Scale (SSQ) [24] was administered to the participants at the study visit to assess subjective hearing performance. The SSQ comprises three sections: 14 items evaluating speech perception, 17 items evaluating spatial hearing, and 18 items evaluating the quality of hearing. Each item is evaluated on a 0–10 scale, with 0 representing 'unable to hear' and 10 representing 'perfect hearing.' All participants were asked to consider their usual everyday listening situations when responding to each SSQ item.

The World Health Organization Disability Assessment Schedule 2.0 (WHODAS 2.0) is a standardized, cross-culturally validated instrument developed by the WHO to measure health and disability across six domains of functioning: cognition, mobility, self-care, getting along, life activities, and participation [25]. It quantifies the level of difficulty experienced by an individual due to a health condition over the past 30 days, providing a profile of functioning that is directly linked to the framework of the International Classification of Functioning, Disability, and Health (ICF).

2.8. Statistical Analysis

Means, standard deviations, and absolute and relative frequencies were used as the descriptive statistics. Normality of data distribution was assessed using visual inspection of histograms and the Shapiro–Wilk test. As most variables were not normally distributed, non-parametric tests were applied.

Group comparisons for continuous variables were performed using the non-parametric Kruskal–Wallis tests, followed, when appropriate, by pairwise Mann–Whitney U tests with Holm adjustment for multiple pairwise comparisons, while the chi-squared test was applied to compare categorical variables.

To further assess whether group differences in auditory emotion recognition were independent of demographic, sensory, and cognitive factors, multivariable linear regression analyses were conducted. Separate regression models were fitted for the total auditory emotion-recognition score and each of the nine emotion-specific scores (Happiness, Sadness, Fear, Anger, Surprise, Disgust, Pleasure, Pain, and Neutral). Group membership (TH, BCI, and UCI) was included as a categorical predictor and age and education level were retained a priori in all models irrespective of statistical significance. The corresponding visual

emotion-recognition score and speech-in-noise performance at +5 dB SNR were considered as additional candidate covariates using backward selection with a removal criterion of $p > 0.05$. Duration of auditory deprivation was not included in the three-group models because this variable is not defined for typical-hearing participants. Adjusted marginal means were subsequently calculated for each group at the mean values of retained covariates.

Model assumptions were evaluated using residual diagnostics. Heteroscedasticity was assessed using the Breusch–Pagan/Cook–Weisberg test, and multicollinearity was evaluated using variance inflation factors (VIFs). Because evidence of heteroscedasticity was observed for some outcomes, heteroskedasticity-robust standard errors were used consistently for the final linear regression models. Key diagnostic findings are summarized in the Section 3.6 below. Given the bounded nature of the emotion-specific scores and the presence of ceiling effects for some outcomes, ordinal logistic regression models were additionally fitted as sensitivity analyses. These models included the same covariates retained in the corresponding final linear regression models and used the typical-hearing group as the reference category. The purpose of these analyses was to assess whether the direction and overall pattern of the between-group findings were robust to treating the emotion-specific scores as ordinal rather than continuous outcomes. The results of the ordinal-regression sensitivity analyses are summarized in the Section 3.6 below.

To account for multiplicity across the emotion-specific analyses, the overall group-effect p-values from the nine emotion-specific primary linear regression models were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. The total auditory score was considered an aggregate outcome and was therefore not included in this FDR family. In addition, pairwise comparisons among the three study groups within each outcome were adjusted using the Bonferroni method.

Additional analyses were conducted within the cochlear implant cohort to specifically examine differences between UCI and BCI users after accounting for clinically relevant hearing-history characteristics. To avoid additional data-driven variable selection in the relatively small implanted cohort, two parsimonious models were specified a priori. The primary within-CI model (Model A) included implant group, education, age at first cochlear implantation, and age at onset of hearing loss. For bilateral CI users, age at implantation was defined as age at first cochlear implantation. A sensitivity model (Model B) included implant group, education, age at first cochlear implantation, and duration of auditory deprivation, replacing age at onset of hearing loss. Both models were estimated using heteroskedasticity-robust standard errors.

For the primary within-CI analyses, Benjamini–Hochberg FDR adjustment was applied across the nine emotion-specific UCI-versus-BCI comparisons from Model A. The total auditory score was not included in this FDR family because it represents an aggregate outcome. FDR adjustment was not applied to Model B because it was prespecified as a sensitivity analysis.

To further assess the potential influence of the age imbalance between groups, an additional age-based sensitivity analysis was performed. Because strict one-to-one age matching was not well supported by the available age distributions, the analysis was restricted to the common age range represented in the TH group (20–57 years). This age-restricted subset included 21 TH, 14 UCI, and 9 BCI participants. The primary total auditory emotion-recognition model was repeated in this subset while retaining age as an adjustment covariate, and model-based pairwise group comparisons were Bonferroni-adjusted.

All statistical analyses were performed using STATA version 19 (StataCorp, College Station, TX, USA). Statistical significance was set at $p < 0.05$.

3. Results

3.1. Sample Characteristics

The demographic, audiological, and clinical characteristics of the sample are summarized in Table 1.

Table 1. Demographic, audiological, and clinical characteristics of the study sample across the three groups.

Variable	TH (n = 21)	UCI (n = 22)	BCI (n = 15)	*p*-Value
Sex, F:M	14:07	11:11	09:06	0.536
Age at evaluation, years	35.5 ± 11.5	56.2 ± 8.1	46.1 ± 19.7	<0.001
Education, years	15.6 ± 3.0	13.6 ± 3.6	14.2 ± 4.0	0.239
Age at onset of hearing loss, years	–	32.7 ± 15.9	23.5 ± 17.4	–
Postlingual hearing loss, n (%)	–	22 (100%)	15 (100%)	–
Age at first cochlear implantation, years	–	50.6 ± 8.2	36.7 ± 22.7	–
Age at second cochlear implantation, years	–	–	42.2 ± 21.1	–
Auditory deprivation, years †	–	17.9 ± 13.1	20.3 ± 13.5	–
Unaided PTA5, dB HL *	10.2 ± 4.5	101 ± 2.5	102 ± 3.4	–
Free-field PTA5, dB HL	11.2 ± 2.2	32.7 ± 3.9	30.4 ± 3.7	<0.001
Speech recognition in quiet, %, 65 dB SPL	100 ± 0.0	90 ± 1.5	92 ± 1.4	–
Speech-in-noise at +5 dB SNR, %	94.3 ± 10.3	47.3 ± 20.5	55.3 ± 16.0	<0.001
Follow-up/bilateral CI experience, months ‡	–	63.3 ± 50.9	46.0 ± 36.8	0.293
Daily device use, hours/day	–	14.4 ± 3.3	13.4 ± 2.9	–
MoCA total score	28.0 ± 1.1	27.7 ± 1.1	26.7 ± 3.7	0.429
WHODAS 2.0 total score	16.0 ± 18.2	19.0 ± 20.5	28.2 ± 35.9	0.583

Demographic, audiological, and clinical characteristics of the study sample across typical-hearing participants (TH), unilateral cochlear implant users (UCI), and bilateral cochlear implant users (BCI). Values are reported as mean ± standard deviation unless otherwise specified. PTA5 = pure-tone average at 250, 500, 1000, 2000, and 4000 Hz; SNR = signal-to-noise ratio; MoCA = Montreal Cognitive Assessment; WHODAS 2.0 = World Health Organization Disability Assessment Schedule 2.0. *p*-values refer to overall between-group comparisons where applicable. * For CI participants, unaided PTA5 values refer to the preoperative audiological assessment. † For BCI users, auditory deprivation corresponds to the longer ear-specific deprivation duration used in the within-CI sensitivity model. ‡ For UCI users, follow-up represents time since cochlear implantation. For BCI users, bilateral CI experience represents time since the second cochlear implantation; the UCI-versus-BCI comparison was performed using the Mann–Whitney U test.

The study included 58 adult participants, divided into three groups: unilateral cochlear implant users (UCI), bilateral cochlear implant users (BCI), and typical-hearing (TH) controls.

The TH group included 21 adults (14 female and 7 male). All TH participants showed normal hearing sensitivity on standard audiometric assessment, with an unaided PTA5 of 10.2 ± 4.5 dB HL. The cochlear implant cohort comprised 37 adults with severe-to-profound SNHL, including 22 UCI users (11 female and 11 male) and 15 BCI users (9 female and 6 male).

A significant between-group difference was observed for age (Kruskal–Wallis, $p < 0.001$). TH participants were significantly younger (mean ± SD: 35.5 ± 11.5 years) than both UCI users (56.2 ± 8.1 years; $p < 0.001$) and BCI users (46.1 ± 19.7 years), whereas no significant age difference was found between unilateral and bilateral CI users ($p = 0.122$). There were no significant between-group differences in sex distribution or educational level ($p = 0.536$ and $p = 0.239$, respectively), with comparable years of formal education among TH participants

(mean ± SD: 15.6 ± 3.0), UCI users (13.6 ± 3.6), and BCI users (14.2 ± 4.0; TH vs. UCI: $p = 0.085$; UCI vs. BCI: $p = 0.065$; TH vs. BCI: $p = 0.451$).

Within the CI cohort, hearing-loss etiology was heterogeneous and included progressive hearing loss of unknown etiology (n = 13), genetic hearing loss (n = 9), otosclerosis (n = 6), sudden hearing loss (n = 6), Ménière's disease (n = 2), and bilateral cochleopathy (n = 1). All CI participants had postlingual hearing loss, and none had a documented history of meningitis. Mean age at onset of hearing loss was 32.7 ± 15.9 years in UCI users and 23.5 ± 17.4 years in BCI users. Mean age at implantation was 50.6 ± 8.2 years in UCI users. In BCI users, mean age at first implantation was 36.7 ± 22.7 years and mean age at second implantation was 42.2 ± 21.1 years. Mean auditory deprivation was 17.9 ± 13.1 years in UCI users and 20.3 ± 13.5 years in BCI users. Mean follow-up in UCI users was 63.3 ± 50.9 months, whereas mean bilateral CI experience, defined as time since the second implantation, was 46.0 ± 36.8 months in BCI users. No subject discontinued CI use. All subjects were implanted with a Nucleus multichannel device (Cochlear Ltd., Sydney, Australia). The mean of daily device use was 14.4 (SD +/− 3.3) h in UCI users and 13.4 (SD +/− 2.9) in BCI users. In the UCI group, twelve subjects wore a CI on one ear and a hearing aid on the opposite side ("bimodal stimulation"), but they were tested with the CI only, with the contralateral ear occluded. Thirteen BCI patients received sequential bilateral CIs with a mean interval of 68 months, and in 2 cases CI was implanted simultaneously.

3.2. Group Differences

PTA differed significantly across groups ($p < 0.001$), with the TH group showing significantly lower (better) thresholds (11.2 ± 2.2 dB HL) than both the UCI (32.7 ± 3.9 dB HL; $p < 0.001$) and BCI (30.4 ± 3.7 dB HL; $p < 0.001$) groups; no significant PTA difference emerged between UCI and BCI users (all $p > 0.05$). CI users showed substantial functional benefit under aided conditions. Mean free-field PTA5 was 32.7 ± 3.9 dB HL in the UCI group and 30.4 ± 3.7 dB HL in the BCI group, compared with unaided PTA5 values of approximately 101 and 102 dB HL, respectively. Speech recognition in quiet at 65 dB SPL was also high, averaging 90% in UCI users and 92% in BCI users. These findings indicate effective auditory access with the cochlear implant, although the present cross-sectional study was not designed as a formal pre- versus post-implant outcome analysis. Speech-in-noise scores also varied significantly across groups at the three SNR conditions tested (+10, +5, and 0 dB) (all omnibus $p < 0.001$), with TH listeners outperforming both CI groups, while UCI and BCI users did not differ significantly from each other (all $p > 0.05$). The duration of auditory deprivation did not differ significantly between UCI and BCI users ($p > 0.05$).

Subjective hearing ability, assessed using the SSQ, showed significantly higher scores in the TH group across all domains (Speech: 8.5 ± 1.3; Spatial: 8.6 ± 1.2; Qualities: 8.6 ± 1.0) compared to both CI groups (UCI-Speech: 5.7 ± 1.7, $p < 0.001$; Spatial: 5.7 ± 2.1, $p < 0.001$; Qualities: 6.2 ± 1.9, $p < 0.001$; BCI-Speech: 6.3 ± 1.7, $p < 0.001$; Spatial: 6.0 ± 1.5, $p < 0.001$; Qualities: 6.6 ± 1.9, $p < 0.001$), with no significant differences between UCI and BCI users.

Global disability, assessed by the WHODAS 2.0, showed no significant differences across groups ($p = 0.583$).

Global cognitive functioning, assessed using the MoCA, revealed no significant differences in total scores across groups ($p = 0.429$). Analysis of MoCA subdomains showed no statistically significant overall between-group difference for the Attention component ($p = 0.071$), although exploratory pairwise comparisons suggested lower scores in BCI users than in UCI users (4.9 ± 1.3 vs. 5.6 ± 0.7; $p = 0.044$) and TH participants (4.9 ± 1.3 vs. 5.7 ± 0.6; $p = 0.038$). No other MoCA subdomains showed significant between-group differences (all $p > 0.40$).

Visual emotion recognition performance did not differ significantly in terms of total score ($p = 0.067$). Pairwise comparisons showed that this trend was primarily driven by BCI users scoring lower than TH participants (41.6 ± 4.7 vs. 44.4 ± 3.7; $p = 0.033$). Emotion-specific analyses revealed significant group differences for fear ($p = 0.024$), with BCI users outperforming UCI users (6.5 ± 1.9 vs. 4.3 ± 2.5; $p = 0.013$), and for anger ($p < 0.001$), with BCI users scoring lower than both UCI users (5.3 ± 1.1 vs. 6.6 ± 1.7; $p = 0.005$) and TH participants (5.3 ± 1.1 vs. 7.4 ± 1.4; $p < 0.001$).

Processing speed for visual emotional stimuli (mean reaction time) differed between groups. CI users showed slower overall reaction time for visual emotional stimuli compared with TH participants, particularly in the UCI group (3953 vs. 3259 ms; $p = 0.008$). Slower processing was most evident for surprise ($p = 0.009$), anger ($p = 0.049$), and disgust ($p = 0.051$).

3.3. Auditory Emotion Recognition Performance

For the total auditory emotion-recognition score, both UCI and BCI users showed significantly lower adjusted performance than TH participants (both Bonferroni-adjusted $p < 0.001$), whereas no significant difference was observed between UCI and BCI users ($p = 0.708$). Adjusted marginal means were 33.76 ± 2.49 for UCI, 30.30 ± 2.06 for BCI, and 58.04 ± 1.88 for TH participants (Table 2).

Table 2. Auditory emotion recognition.

Outcome	UCI Adjusted Mean ± SE	BCI Adjusted Mean ± SE	TH Adjusted Mean ± SE	BH-FDR *p* *	UCI vs. TH *p* †	BCI vs. TH *p* †	UCI vs. BCI *p* †	Additional Covariate Retained ‡
Happiness	7.78 ± 0.54	7.13 ± 0.44	9.24 ± 0.43	0.023	0.203	0.012	0.888	None
Sadness	5.20 ± 0.69	5.70 ± 0.66	7.45 ± 0.64	0.056	0.128	0.115	1.000	None
Fear	2.61 ± 0.36	1.96 ± 0.57	4.71 ± 0.40	0.004	0.006	0.003	0.809	None
Anger	2.12 ± 0.34	2.73 ± 0.50	4.97 ± 0.38	<0.001	<0.001	0.003	0.997	Visual anger score
Surprise	3.21 ± 0.50	2.02 ± 0.43	3.90 ± 0.58	0.024	1.000	0.035	0.232	None
Disgust	3.28 ± 0.48	2.81 ± 0.46	8.33 ± 0.32	<0.001	<0.001	<0.001	1.000	None
Pleasure	4.12 ± 0.67	2.28 ± 0.51	5.75 ± 0.53	<0.001	0.282	<0.001	0.070	None
Pain	3.18 ± 0.48	3.04 ± 0.49	5.22 ± 0.55	0.024	0.055	0.020	1.000	None
Neutral	3.06 ± 0.77	3.17 ± 0.76	8.00 ± 0.52	<0.001	<0.001	<0.001	1.000	Visual neutral score
Total	33.76 ± 2.49	30.30 ± 2.06	58.04 ± 1.88	–	<0.001	<0.001	0.708	None

Auditory emotion recognition: adjusted marginal means and corrected between-group comparisons. Values are adjusted marginal means ± standard error (SE) estimated from the final robust multivariable linear regression models. All primary models included study group, age, and education a priori. * Benjamini–Hochberg false discovery rate (BH-FDR) correction was applied to the overall group-effect *p*-values across the nine emotion-specific outcomes. The total score was treated as an aggregate outcome and was not included in the FDR family. † Pairwise *p*-values are Bonferroni-adjusted for the three model-based group comparisons performed within each outcome. ‡ The corresponding visual emotion-recognition score and speech-in-noise performance at +5 dB SNR were evaluated as additional candidate covariates. Only visual anger and visual neutral scores were retained in the corresponding final models; SNR +5 dB was not retained in any final primary model. Adjusted marginal means for the individual emotions are model-specific estimates and are not expected to sum exactly to the adjusted total score because each outcome was estimated in a separate regression model. TH = typical hearing; UCI = unilateral cochlear implant; BCI = bilateral cochlear implant.

Across the nine emotion-specific primary models, the overall group effect remained statistically significant after Benjamini–Hochberg FDR correction for eight outcomes: Happiness (pFDR = 0.023), Fear (pFDR = 0.004), Anger (pFDR < 0.001), Surprise (pFDR = 0.024),

Disgust (pFDR < 0.001), Pleasure (pFDR < 0.001), Pain (pFDR = 0.024), and Neutral (pFDR < 0.001). Sadness did not remain statistically significant after FDR correction (pFDR = 0.056).

Bonferroni-adjusted pairwise comparisons showed significantly lower performance than TH participants in both CI groups for Fear, Anger, Disgust, and Neutral. For Happiness, Surprise, Pleasure, and Pain, significant differences from TH participants were observed for BCI users only. No UCI-versus-BCI pairwise comparison was statistically significant for any emotion-specific outcome after Bonferroni adjustment.

The analysis of subjective valence ratings of the auditory stimuli revealed emotion-specific differences among groups (Figure 1). Valence was rated on a 0–10 scale, with lower values indicating more negative and higher values indicating more positive perceived affect.

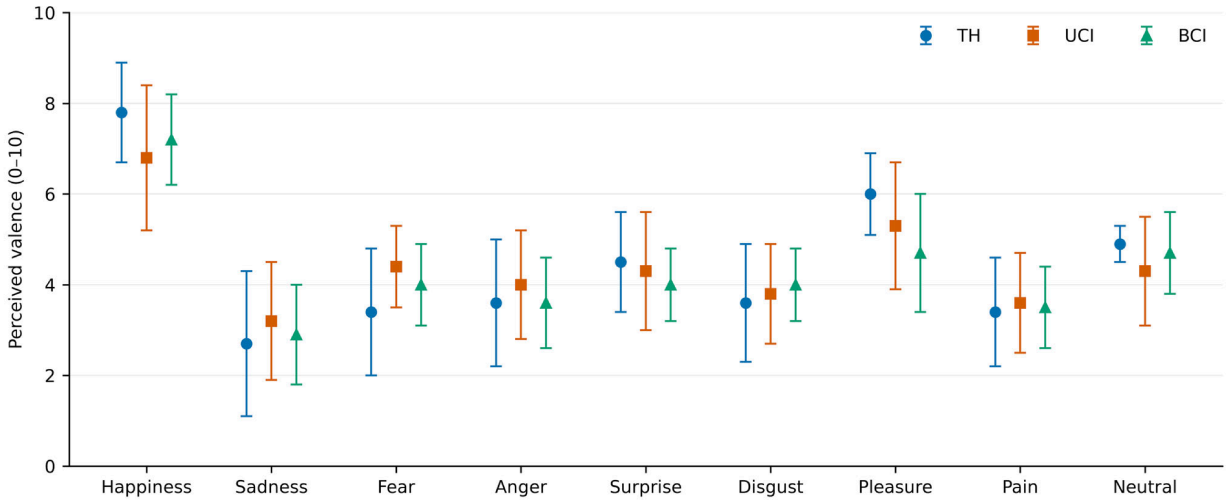

Figure 1. Subjective valence ratings for auditory emotional stimuli across groups. Values are presented as mean ± SD on a 0–10 scale, with lower scores indicating more negative and higher scores indicating more positive perceived affect. Holm-adjusted pairwise comparisons were statistically significant for Fear (UCI vs. TH, $p = 0.025$) and Pleasure (UCI vs. TH, $p = 0.018$; BCI vs. TH, $p = 0.006$). No other adjusted pairwise comparison was statistically significant. TH = typical hearing; UCI = unilateral cochlear implant; BCI = bilateral cochlear implant.

Mean valence ratings were as follows: Happiness, 6.75 ± 1.61 in UCI, 7.24 ± 1.01 in BCI, and 7.79 ± 1.05 in TH participants; Sadness, 3.21 ± 1.29, 2.86 ± 1.13, and 2.75 ± 1.65, respectively; Fear, 4.38 ± 0.85, 4.02 ± 0.93, and 3.44 ± 1.40; Anger, 4.01 ± 1.16, 3.59 ± 1.03, and 3.56 ± 1.43; Surprise, 4.30 ± 1.31, 3.95 ± 0.79, and 4.54 ± 1.07; Disgust, 3.79 ± 1.05, 4.00 ± 0.83, and 3.56 ± 1.26; Pleasure, 5.25 ± 1.41, 4.75 ± 1.31, and 6.04 ± 0.91; Pain, 3.57 ± 1.06, 3.51 ± 0.86, and 3.42 ± 1.20; and Neutral, 4.32 ± 1.25, 4.67 ± 0.89, and 4.92 ± 0.38, respectively.

The omnibus group effect was statistically significant for Fear (Kruskal–Wallis $p = 0.017$) and Pleasure ($p = 0.003$), whereas no significant overall group effect was observed for the remaining valence ratings. Holm-adjusted pairwise comparisons showed higher Fear valence ratings in UCI than in TH participants (adjusted $p = 0.025$). For Pleasure, both UCI and BCI participants provided lower valence ratings than TH participants (adjusted $p = 0.018$ and $p = 0.006$, respectively). No other Holm-adjusted pairwise comparison was statistically significant.

3.4. Direct Comparison of Unilateral Versus Bilateral Cochlear Implant Recipients

The UCI and BCI groups did not differ significantly in age, education, or the principal audiological performance measures examined. Mean follow-up in UCI users was

63.3 ± 50.9 months, whereas mean bilateral CI experience, defined as time since the second implantation, was 46.0 ± 36.8 months in BCI users; this difference was not statistically significant (Mann–Whitney $p = 0.293$). The within-CI analyses provided no robust evidence of a consistent difference in auditory emotion recognition between UCI and BCI users. The total auditory score did not differ significantly between groups (adjusted UCI-versus-BCI difference, β = 4.13; 95% CI, −2.03 to 10.28; $p = 0.181$), and no emotion-specific UCI-versus-BCI comparison remained statistically significant after FDR correction.

3.5. Multivariable Regression Models

In the primary multivariable models, study group, age, and education were included a priori in all models, while the corresponding visual emotion-recognition score and speech-in-noise performance at +5 dB SNR were evaluated as additional candidate covariates. Heteroskedasticity-robust standard errors were used throughout.

For the total auditory emotion-recognition score, both UCI and BCI users performed significantly worse than TH participants (both $p < 0.001$). Older age was associated with lower total performance (β = −0.261, $p = 0.007$), whereas higher education was associated with better performance (β = 0.912, $p = 0.006$).

Among the emotion-specific models, higher education was positively associated with Fear recognition (β = 0.141, $p = 0.034$) and Pain recognition (β = 0.210, $p = 0.002$), whereas older age was associated with poorer Pleasure recognition (β = −0.069, $p = 0.001$). The corresponding visual emotion-recognition score was retained as an additional covariate for Anger (β = 0.305, $p = 0.032$) and Neutral (β = 0.629, $p = 0.022$), with better visual recognition associated with better auditory recognition of the same emotion. Speech-in-noise performance at +5 dB SNR was not retained in any final primary model.

Duration of auditory deprivation was not included in the three-group primary models because it is specific to cochlear implant recipients. In the CI-only sensitivity model including deprivation (Model B), auditory deprivation was not significantly associated with any outcome, including Surprise (β = 0.042, $p = 0.096$).

Full regression coefficients, standard errors, and 95% confidence intervals for all models are reported in Table 3.

Table 3. Multivariable regression models for auditory emotion recognition scores.

Outcome	Predictor	β	Robust SE	95% CI	*p*-Value
Total	UCI vs. TH	−24.273	3.717	−31.732 to −16.815	<0.001
	BCI vs. TH	−27.738	3.155	−34.069 to −21.406	<0.001
	Age	−0.261	0.093	−0.447 to −0.074	0.007
	Education	0.912	0.318	0.275 to 1.550	0.006
Happiness	UCI vs. TH	−1.459	0.782	−3.028 to 0.110	0.068
	BCI vs. TH	−2.117	0.703	−3.527 to −0.707	0.004
	Age	−0.035	0.021	−0.076 to 0.007	0.099
	Education	−0.021	0.070	−0.162 to 0.120	0.767
Sadness	UCI vs. TH	−2.249	1.083	−4.423 to −0.076	0.043
	BCI vs. TH	−1.756	0.826	−3.413 to −0.099	0.038
	Age	−0.048	0.024	−0.096 to 0.001	0.054
	Education	0.167	0.108	−0.049 to 0.383	0.127

Table 3. *Cont.*

Outcome	Predictor	β	Robust SE	95% CI	*p*-Value
Fear	UCI vs. TH	−2.101	0.643	−3.391 to −0.812	0.002
	BCI vs. TH	−2.751	0.782	−4.320 to −1.182	<0.001
	Age	−0.036	0.019	−0.074 to 0.003	0.068
	Education	0.141	0.065	0.011 to 0.272	0.034
Anger	UCI vs. TH	−2.845	0.555	−3.959 to −1.731	<0.001
	BCI vs. TH	−2.237	0.636	−3.514 to −0.960	<0.001
	Age	−0.003	0.019	−0.041 to 0.036	0.884
	Education	0.039	0.060	−0.081 to 0.158	0.517
	Visual anger score	0.305	0.139	0.027 to 0.583	0.032
Surprise	UCI vs. TH	−0.695	0.855	−2.410 to 1.020	0.420
	BCI vs. TH	−1.884	0.720	−3.330 to −0.439	0.012
	Age	0.001	0.019	−0.038 to 0.039	0.973
	Education	0.098	0.077	−0.057 to 0.253	0.209
Disgust	UCI vs. TH	−5.045	0.647	−6.344 to −3.746	<0.001
	BCI vs. TH	−5.514	0.674	−6.866 to −4.161	<0.001
	Age	−0.022	0.020	−0.062 to 0.018	0.274
	Education	0.079	0.076	−0.075 to 0.232	0.309
Pleasure	UCI vs. TH	−1.628	0.954	−3.543 to 0.287	0.094
	BCI vs. TH	−3.474	0.800	−5.078 to −1.869	<0.001
	Age	−0.069	0.020	−0.109 to −0.028	0.001
	Education	0.088	0.087	−0.087 to 0.263	0.316
Pain	UCI vs. TH	−2.032	0.835	−3.707 to −0.357	0.018
	BCI vs. TH	−2.174	0.769	−3.717 to −0.632	0.007
	Age	−0.010	0.019	−0.049 to 0.029	0.594
	Education	0.210	0.066	0.077 to 0.342	0.002
Neutral	UCI vs. TH	−4.943	1.089	−7.129 to −2.757	<0.001
	BCI vs. TH	−4.830	1.092	−7.023 to −2.637	<0.001
	Age	−0.027	0.032	−0.092 to 0.037	0.397
	Education	0.180	0.102	−0.024 to 0.383	0.083
	Visual neutral score	0.629	0.267	0.093 to 1.165	0.022

Primary multivariable regression models for auditory emotion-recognition outcomes. Regression coefficients (β), heteroskedasticity-robust standard errors (SEs), 95% confidence intervals (CI), and unadjusted coefficient-level *p*-values are reported. TH was the reference group for the group coefficients. Study group, age, and education were included a priori in all primary models. The corresponding visual emotion-recognition score and speech-in-noise performance at +5 dB SNR were evaluated as additional candidate covariates; only visual anger and visual neutral scores were retained in the respective final models. Overall emotion-specific group effects and multiplicity-adjusted pairwise comparisons are reported separately in Table 2. TH = typical hearing; UCI = unilateral cochlear implant; BCI = bilateral cochlear implant.

3.6. Supplementary Analyses

Initial univariable analyses showed significant positive associations between the total auditory score and self-reported abilities in the speech, spatial, and sound qualities domains (all $p < 0.001$). However, these associations lost statistical significance after adjustment for group membership (all $p \geq 0.202$). Analysis of visual emotion recognition speed found no

significant effect of group ($p = 0.839$) after adjusting for age, which was itself a significant positive predictor ($p = 0.003$).

An additional age-based sensitivity analysis was performed to evaluate whether the marked age imbalance between the TH and CI groups accounted for the primary group difference in auditory emotion recognition. Restricting the analysis to participants within the TH age range of 20–57 years retained 21 TH, 14 UCI, and 9 BCI participants. After restriction and adjustment for age, the total auditory emotion-recognition score remained significantly lower in both CI groups than in TH participants (adjusted difference: UCI vs. TH, −20.19, Bonferroni-adjusted $p < 0.001$; BCI vs. TH, −28.21, $p < 0.001$), whereas the UCI-versus-BCI difference remained non-significant (adjusted difference, 8.03; $p = 0.201$). These findings indicate that the marked difference in the primary total score persisted within the common age range, although residual confounding by age cannot be excluded.

Model diagnostics showed evidence of heteroscedasticity for Fear (Breusch–Pagan $p = 0.022$) and Neutral ($p < 0.001$), whereas no evidence of heteroscedasticity was observed for the remaining primary outcomes. Maximum variance inflation factors were low ($\leq$2.03), indicating no relevant multicollinearity. Heteroskedasticity-robust standard errors were therefore retained for all primary linear models. Ordinal logistic regression sensitivity analyses of the emotion-specific scores showed a broadly consistent direction and overall pattern of group effects compared with the primary linear models, supporting the robustness of the main conclusions to the bounded nature of the outcomes.

4. Discussion

The present study evaluated auditory emotion recognition using the MAV in adults with UCI, BCI, and TH. The main findings can be summarized as follows: (i) both CI groups showed markedly poorer auditory emotion-recognition performance than TH participants, with total scores approximately half those observed in the TH group; (ii) no consistent statistically significant difference between UCI and BCI users was identified after adjustment for multiple testing; (iii) age and education were associated with performance for selected auditory emotion-recognition outcomes; and (iv) visual emotion-recognition scores for Anger and Neutral were positively associated with auditory recognition of the corresponding emotions. Overall, these findings demonstrate a marked association between cochlear implant use and reduced auditory emotion recognition compared with typical hearing, while the present study does not identify the specific acoustic mechanisms underlying this difference.

It should be noted that unlike most paradigms that employ semantically meaningful utterances, the Montreal Affective Voices (MAV) consist of nonverbal affective vocal bursts that are structurally more similar to the stimuli used in visual emotion research (e.g., Ekman faces) than to emotionally inflected speech, thereby allowing a more direct comparison across sensory modalities in the study of emotion recognition [8,19,26].

4.1. Emotional Prosody Recognition: CI Users Versus Typical Hearing Controls

Consistent with prior studies [27–29], both CI groups showed profound deficits in emotional prosody recognition. Total scores for CI users were approximately half those of TH controls across all emotional categories. This pattern aligns with meta-analytic evidence indicating that emotional prosody identification is more severely compromised by electric hearing than is linguistic prosody, primarily due to inadequate transmission of fundamental frequency (F0) cues through the degraded CI signal [27].

Not all emotions were equally affected. Happiness was recognized most accurately, followed by sadness, while fear, anger, neutral expressions, and especially surprise proved most challenging for CI users [28,30–32]. Previous studies have reported confusion between

acoustically or conceptually similar emotions, including fear and surprise and, in some contexts, pleasure and happiness [32]. Although confusion patterns were not specifically analyzed in the present study, these findings from the literature highlight the potential value of future analyses examining emotion-specific error patterns and their acoustic correlates.

It should also be noted that recognition performance in the present TH group was lower for some emotion categories than reported in the original MAV validation study. Belin et al. reported an overall mean recognition accuracy of approximately 68%, with hit rates of 56% for Fear and 75% for Surprise [19], whereas the corresponding adjusted means in the present TH group were 4.71/10 and 3.90/10, respectively. We did not identify published Italian normative or validation data for the MAV against which these values could be directly benchmarked. Differences in sample characteristics, cultural context, and administration may therefore contribute to the observed divergence, and emotion-specific comparisons with the original validation sample should be interpreted cautiously.

Faced with degraded spectrotemporal input, CI users tend to rely disproportionately on secondary acoustic cues (intensity and duration), which are insufficient to fully compensate for altered pitch perception [33–35]. At the multimodal integration level, CI users also tend to overweight semantic content compared to TH individuals when prosodic and verbal cues conflict, reflecting an adaptive compensatory strategy rather than a primary cognitive deficit [36,37]. Strengthening access to residual spectral and temporal signals and training explicit compensatory strategies represent key goals for rehabilitation [38,39].

4.2. Unilateral Versus Bilateral Cochlear Implantation

Direct comparisons between UCI and BCI users did not identify a consistent statistically significant difference in auditory emotion recognition in the present sample. The adjusted total-score difference was not significant, and none of the emotion-specific UCI-versus-BCI comparisons remained significant after FDR correction in the prespecified within-CI analysis. These findings should not be interpreted as evidence of equivalence or as demonstrating absence of benefit from bilateral implantation, because the study was not designed as a non-inferiority or equivalence trial and the modest group sizes limit the precision of between-group comparisons.

Mean follow-up in UCI users was 63.3 ± 50.9 months, whereas mean bilateral CI experience, defined as time since the second implantation, was 46.0 ± 36.8 months in BCI users; this difference was not statistically significant (Mann–Whitney $p = 0.293$).

The absence of a robust UCI-versus-BCI difference in emotional prosody recognition contrasts with the established benefits of bilateral implantation for other auditory functions, including speech perception in noisy conditions and sound localization [40]. However, the present study did not directly assess the acoustic or psychoacoustic mechanisms underlying emotion-specific performance, and therefore no mechanistic inference regarding spectral, temporal, or binaural processing can be made from these data alone.

No emotion-specific UCI-versus-BCI comparison remained statistically significant after correction for multiple testing. Clinical decisions regarding unilateral versus bilateral implantation should therefore continue to be based on established clinical indications and expected functional benefits rather than on the present emotional-prosody findings alone.

4.3. Predictors of Auditory Emotion Recognition

Beyond CI group membership, multivariable regression analyses showed that age and education were associated with performance for selected outcomes after adjustment for study group. Older age was associated with lower total auditory emotion-recognition scores and poorer Pleasure recognition, whereas higher education was associated with better total, Fear, and Pain recognition. These findings are broadly consistent with previous

evidence linking age and educational background to variability in emotion-recognition performance [41,42]; however, these associations should be interpreted cautiously and not as evidence of causal or independent determinants. Speech-in-noise performance at +5 dB SNR was not retained as an additional covariate in any final primary three-group model. This finding does not establish that speech-in-noise ability or listening experience is unrelated to emotional prosody recognition, although duration of device use has been shown to predict emotion identification in studies with wider experience ranges [29,43].

For anger and neutral expression recognition, higher visual emotion recognition scores were positively associated with auditory performance after adjustment for group, age, and education. This cross-modal association may indicate some shared variability between visual and auditory emotion processing; however, the present cross-sectional data do not allow the underlying mechanism to be determined [44].

4.4. Perceived Emotional Valence

Subjective valence ratings showed a more limited pattern of between-group differences than emotion-recognition accuracy. UCI participants provided higher valence ratings for Fear than TH participants, whereas both CI groups provided lower valence ratings for Pleasure than TH participants after adjustment for pairwise comparisons. No significant adjusted group differences were observed for the other emotion categories. These findings suggest that cochlear implant use may be associated not only with reduced accuracy of emotion identification but also with differences in the subjective affective evaluation of selected vocal emotions. However, the present data do not support a generalized alteration or compression of valence perception across emotions, and the mechanisms underlying these emotion-specific differences cannot be determined from this study.

Previous studies have also reported differences in affective responses to auditory stimuli in listeners with hearing loss or cochlear implants. Hearing-aid and bimodal CI listeners have shown less extreme emotional ratings for non-speech sounds than listeners with typical hearing [45], while experimentally simulated cochlear-implant spectral degradation has been associated with altered emotional responses to environmental sounds [46]. Differences in emotional responses have also been reported in bilateral CI users for musical stimuli [47,48]. Although these findings provide a broader context for the present valence results, differences in stimulus type and experimental paradigm preclude direct comparison, and the present study does not establish the acoustic mechanisms underlying the observed emotion-specific effects.

4.5. Visual Emotion Recognition

Visual emotion-recognition performance showed relatively limited between-group differences compared with the marked auditory emotion-recognition deficits. The overall group comparison for the total visual score did not reach statistical significance ($p = 0.067$), although an exploratory pairwise comparison suggested lower performance in BCI than in TH participants. Emotion-specific differences were observed for Fear and Anger, with BCI users showing higher Fear recognition than UCI users and lower Anger recognition than both UCI and TH participants. These findings should be interpreted cautiously because the emotion-specific visual comparisons were secondary analyses, although they are broadly consistent with previous reports of subtle visual-affective differences in CI populations [49].

Reaction-time measures suggested slower visual emotion processing in CI users, particularly for Surprise and Anger, while Disgust showed only a borderline between-group difference ($p = 0.051$). Previous behavioral and neurophysiological studies have reported increased processing demands for socio-emotional cues in CI populations [44,50,51].

However, the present behavioral data do not allow conclusions regarding the underlying neural mechanisms.

4.6. Global Cognition, Disability, and Quality of Life

The CI cohort was significantly older than the TH group, and age may therefore have contributed to the observed differences in auditory emotion recognition. Global MoCA scores did not differ significantly across groups; however, this finding should be interpreted cautiously because the MoCA contains auditory and verbal components [52], even though CI participants were tested in the best-aided condition with written and visual support. Previous studies have reported stabilization or improvement in global cognitive performance following cochlear implantation in some older adults [53–55].

The omnibus between-group comparison for the MoCA Attention subdomain was not statistically significant ($p = 0.071$). Although exploratory pairwise comparisons suggested lower Attention scores in BCI users, these findings should not be interpreted as evidence of a specific cognitive vulnerability and require cautious interpretation [53–55].

Global disability, as assessed by the WHODAS 2.0, did not differ significantly across groups. This finding indicates that the marked differences observed in auditory emotion recognition were not accompanied by measurable between-group differences in global disability in the present sample. Previous studies have reported improvements in hearing-related quality of life and social participation following cochlear implantation [54,56,57]. More specific measures of socio-emotional functioning may nevertheless be needed to determine whether deficits in emotional prosody recognition are associated with real-world communication or participation difficulties.

4.7. Clinical Implications

The present findings, together with converging evidence, indicate that substantial difficulties in vocal emotion recognition may persist in adults with cochlear implants, with no consistent statistically significant advantage of bilateral over unilateral implantation detected in the present sample [12,39,44]. Rehabilitation approaches may therefore benefit from extending beyond speech intelligibility to include targeted emotion-perception and multimodal audiovisual training, which has been investigated as a means of supporting vocal emotion recognition and socio-emotional communication [12,38,39,44].

The present findings do not identify a specific acoustic mechanism responsible for the observed deficit. Nevertheless, they support further investigation of technological approaches aimed at improving access to acoustic information relevant to emotional prosody, together with individualized rehabilitation strategies. Clinical follow-up may also benefit from attention to socio-emotional communication difficulties that are not necessarily captured by conventional measures of speech perception or global disability. More comprehensive models integrating auditory, demographic, cognitive, and affective factors may help refine counseling and expectations regarding emotional communication outcomes after cochlear implantation.

4.8. Limitations

Several limitations should be considered when interpreting the present findings. First, the cross-sectional design precludes causal inference and does not allow the effects of cochlear implantation to be separated from those of the underlying hearing loss, previous auditory experience, or other forms of auditory rehabilitation. The absence of a hearing-impaired non-implanted comparison group therefore limits attribution of the observed between-group differences specifically to cochlear implant use.

Second, the groups differed substantially in age, with mean ages of 35.5 ± 11.5 years in TH participants, 56.2 ± 8.1 years in UCI users, and 46.1 ± 19.7 years in BCI users. Age was therefore included a priori in all primary multivariable models together with education; nevertheless, residual confounding cannot be excluded. The CI cohort was also clinically heterogeneous with respect to hearing-loss etiology and implantation history, which may have introduced additional variability.

Third, no a priori sample-size or power calculation was performed. The modest and unequal sample sizes, particularly for the direct UCI-versus-BCI comparison (n = 22 and n = 15, respectively), may have limited the ability to detect smaller between-group effects and restricted subgroup analyses. No formal non-inferiority or equivalence analysis was performed; therefore, non-significant UCI-versus-BCI comparisons should not be interpreted as evidence of equivalence or as demonstrating absence of benefit from bilateral implantation.

Fourth, multiple testing was addressed in the analyses using the Benjamini–Hochberg false discovery rate procedure across the nine emotion-specific primary outcomes and Bonferroni adjustment for the three model-based pairwise group comparisons within each outcome. Nevertheless, given the modest sample size and the number of outcomes examined, emotion-specific findings should still be interpreted cautiously.

Fifth, the emotion-specific outcomes are bounded scores and some distributions approached ceiling values in the TH group. Model assumptions were therefore assessed using residual diagnostics, heteroscedasticity testing, and variance inflation factors, and heteroskedasticity-robust standard errors were used throughout the final linear models. Ordinal-regression sensitivity analyses yielded broadly consistent findings; however, residual model uncertainty remains because of the limited sample size.

In addition, no Italian normative dataset was available for direct benchmarking of the MAV results, and the 55-item visual emotion-recognition task was used as a secondary behavioral measure rather than as a formally validated Italian version of the original FEIT; these factors should be considered when interpreting emotion-specific visual and auditory performance.

Finally, the study relied predominantly on behavioral measures and did not include psychoacoustic, acoustic, or neurophysiological assessments. Consequently, the present data cannot determine the specific acoustic or neural mechanisms underlying impaired emotional prosody recognition.

4.9. Future Directions

Future research should combine behavioral testing with neurophysiological methods such as EEG or fMRI to clarify the neural mechanisms associated with emotion processing in cochlear implant users [39]. Longitudinal studies following participants from pre-implantation through longer-term follow-up could help characterize changes in emotional prosody recognition over time and identify factors associated with individual variability. Intervention studies should also evaluate targeted emotion-perception and multimodal audiovisual training and assess whether improvements generalize to real-world communication and quality of life. Finally, larger multicenter samples would allow more robust evaluation of the relative contributions of age, education, hearing history, speech-recognition performance, and other clinical factors to auditory emotion recognition and subjective valence perception.

5. Conclusions

This study found substantially poorer auditory emotion-recognition performance in adults with unilateral and bilateral cochlear implants compared with typical-hearing participants. After adjustment for relevant covariates and multiple testing, no consistent

statistically significant difference between UCI and BCI users was identified in the present sample. These findings should not be interpreted as evidence of equivalence between unilateral and bilateral implantation, as no formal non-inferiority or equivalence analysis was performed.

Subjective valence ratings showed more limited between-group differences, with significant adjusted differences confined to Fear and Pleasure rather than indicating a generalized alteration of affective evaluation. Age and education were associated with selected auditory emotion-recognition outcomes, while visual emotion-recognition scores were positively associated with auditory performance for Anger and Neutral.

Overall, the findings demonstrate a marked association between cochlear implant use and reduced auditory emotion recognition compared with typical hearing, while the specific acoustic and neural mechanisms underlying this deficit cannot be determined from the present data. Future studies should further investigate technological and rehabilitative approaches aimed at improving access to acoustic information relevant to emotional prosody and supporting socio-emotional communication in cochlear implant users.

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