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Otology

Intonational cues for speech perception in noise by cochlear implant listeners

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Abstract

Purpose

The objectives of this study are to evaluate cochlear implant (CI) listeners' ability to infer low frequency (LF) pitch information from temporal fine structure (TFS) cues and to gain insight into its effects on speech perception, especially in the presence of a fluctuating background noise. Pitch perception assessment using linguistic stimuli is believed to better reflect the role of pitch in communicatively realistic situations.

AQ1

Methods

The low-pass-filtered sentence intonation (SI-LPF) test based on linguistic stimuli marked by intonation changes is used to estimate a difference limen for discrimination of LF pitch changes in adult CI listeners ($N = 17$ ears). Speech perception in the presence of noise is assessed using the sentence test with adaptive randomized roving level (STARR), where everyday sentences are presented at low, medium, and high levels in a fluctuating background noise. SI-LPF correlations with STARR are compared to those with sentence recognition tests presented in quiet (SRQ) and in noise, using fixed signal-to-noise ratio (SNRs at +10 and +5 dB).

Results

SI-LPF findings show significant positive correlations with STARR performance ($r_s = 0.63$, $p = 0.007$), whilst the associations with SRQ ($r_s = -0.37$, $p = 0.149$), SNR + 10 ($r_s = -0.24$, $p = 0.345$), and SNR + 5 ($r_s = -0.14$, $p = 0.587$) are not statistically significant.

Conclusions

Present findings reflecting considerably stronger correlations than previous studies using non-linguistic stimuli, in particular for speech perception with roving-level adaptive test method (STARR) highlight the effects of LF pitch perception and TFS sensitivity on challenging everyday situations, where CI users listen to speakers with varying levels in a fluctuating background.

Keywords

Pitch perception

Intonation perception
Speech perception in noise
Cochlear implants
Temporal fine structure

Introduction

People with normal hearing (NH) have the perceptual ability to distinguish the target speech from the competing noise even in a fluctuating background which is typically present in everyday listening situations. This skill is also known as “listening in the dips” and is believed to be linked to the ear’s temporal fine structure (TFS) sensitivity. The extent to which cochlear implant (CI) listeners are able to perceive the TFS information is unclear. In conventional CI sound coding strategies, only the temporal envelope cues are preserved with the TFS cues being mostly omitted. Research suggests that temporal envelope cues alone are insufficient to allow the perceptual segregation of mixtures of sounds; and the TFS information may be more important than the envelope cues for the fundamental frequency (F0) information, for frequencies lower than 1000 Hz, for pitch perception especially in the low frequency (LF) domain and for understanding speech in a fluctuating background. Indeed, CI listeners’ difficulties for challenging everyday communication where they usually face a variety of speakers in a fluctuating background noise are thought to partly stem from this poor low-frequency (LF) pitch perception linked to reduced TFS processing [1, 2, 3, 4, 5, 6, 7].

In recent years, there has been growing interest in the area of pitch perception of CI users. Consequently, a remarkable increase in the number of scientific studies has been observed in this area [7, 8, 9, 10]. In fact, the vast majority of these studies have investigated perception of pitch using non-speech stimuli such as tone complexes. However, non-speech tests may overestimate a listener’s perception of pitch due to differences in the processing of speech versus non-speech stimuli, and, therefore, may not be fully representative of the effects of pitch perception in linguistic contexts or in communicatively realistic situations [11, 12, 13].

The auditory speech sounds evaluation (A&E) suite involves a new psychoacoustic test, the sentence intonation (SI), to evaluate listeners’ pitch perception in a linguistic context and to allow insights into how well F0 is processed in speech stimuli. More precisely, the SI test is addressing clause typing by changes only in pitch, i.e. whether a phrase is a statement or a question [12, 13]. Indeed, several

languages including Italian mark clause typing basically in function of intonation changes. For instance, a phrase like “*La porta è aperta./?*” through intonation changes may indicate either that the door is open or alternatively may question whether the door is open. A question is associated with a high boundary tone whilst a statement is associated with a low one [13, 14]. CI users in comparison to NH listeners are known to identify less accurately clause typing [12, 13, 15].

AQ2

The SI test is available in two modes: non-filtered SI and low-pass-filtered SI (SI-LPF). In the non-filtered mode, high-frequency (HF) cues are available in the speech stimuli. On the other hand, the LPF mode maintains only frequencies in which the F0 is contained, whilst suppressing the higher harmonics. The SI test is validated for adult Italian, Dutch, or Romanian speaking NH people. Normative data from listeners of these three different language backgrounds do not reveal any statistically significant differences, indicating F0 as the most important cue for clause typing in these languages [13]. SI findings in people with hearing impairment highlight that even the listeners with normal pure tone thresholds in the LF range, but with hearing loss in the HF range shows significantly poorer performance than NH people. Performance from listeners with LF hearing loss becomes even significantly worse than both groups, confirming larger negative effects of a hearing loss in the LF range on pitch perception, especially for testing in the LPF mode. Despite a quite large variability within the group, the poorest outcomes are observed in CI users. Indeed, most CI listeners seem not to be able to perceive even the largest difference limen that the SI test offers, reflecting CI users’ great difficulties in performing this intonational test [12].

AQ3

The present study in Italian-speaking CI listeners aims to investigate the effects of LF pitch perception on speech recognition performance. For the evaluation of LF pitch perception in a linguistic context, the SI test is used in the LPF mode [12, 13]. SI findings in association with speech perception performance are so far not reported. The newly developed sentence test with adaptive randomized roving level (STARR) [16, 17] is used as a primary tool for the assessment of speech perception in noise. This adaptive test sets out to avoid either floor or ceiling effects by manipulating the signal-to-noise ratio (SNR) to maintain a listener’s score at a central point of her/his psychometric curve. Sentences are presented at a roving level, whilst the noise is adapted to estimate an SNR at which the listener achieves a speech reception threshold (SRT). This innovative test approach attempts to give a realistic estimate for everyday listening situations where speech levels may vary

in a fluctuating background noise [16, 17, 18]. The STARR test is particularly sensitive to lower level speech and is able to reveal performance differences that are not shown when traditional tests with a fixed presentation level and a fixed SNR are used [19, 20]. Hence, the associations between the SI and STARR findings are studied comparatively with speech perception tests typically presented in quiet, or with a fixed SNR method [21]. Significant correlations are expected in particular with STARR findings since SI-LPF findings are believed to be linked to the listener's ability to infer pitch information from TFS cues that are particularly important for speech perception in a fluctuating background [3].

Materials and methods

Participants

The study group consisted of 13 unilateral and two bilateral CI listeners (8 female and 7 male). The unilateral CI listeners were not using any hearing aids in the contralateral ear. One of the bilateral listeners had a simultaneous implantation in both ears, whilst the second one underwent a sequential implantation with an interval of 5 months between both surgeries. Assessment was performed in a total of 17 ears, all implanted with Med-El devices (Concerto implants and Flex28 electrodes fitted either with OPUS 2 or RONDO processors). All participants were Med-El FS4 users.

The mean age was 46 years (range 18 to 80 years, SD = 21). All participants were native Italian speakers with postlingual onset of deafness. The average duration of profound deafness before implantation was 96.3 months (range 3 to 384 months, SD = 125.5). The minimum duration of CI use was 6 months (mean = 16.8 months, SD = 10.6). The mean aided pure tone threshold at octave frequencies from 125 to 8000 Hz was 34.4 dB HL (range 27.9–40 dB HL, SD = 3.8). The participants did not show any degree of LF residual hearing that may have interfered with SI-LPF outcomes (unaided hearing thresholds above 80 dB HL for frequencies 125–1000 Hz in either ear). Demographic information and audiological outcomes for the participants are given in Tables 1 and 2, respectively.

Table 1

Demographic information for the participants

ID	Age (years)	Gender	CI ear	Duration of deafness (months)	CI use (months)	Pure tone average (dB HL)	Processor

ID	Age (years)	Gender	CI ear	Duration of deafness (months)	CI use (months)	Pure tone average (dB HL)	Processor
P1	37	M	R	3	9	38.6	Rondo
P2	73	F	R	120	10	39.7	Opus2
P3	62	M	R	12	9	35.7	Opus2
P4	56	F	L	4	19	34.3	Opus2
P5	18	M	R	3	8	30.0	Opus2
			L	3	8	30.0	Opus2
P6	68	F	L	12	11	37.1	Opus2
P7	62	M	R	360	19	36.4	Opus2
P8	18	F	L	120	41	34.3	Opus2
P9	37	F	R	216	11	40.0	Rondo
			L	216	6	35.7	Rondo
P10	35	F	R	384	25	27.9	Opus2
P11	68	F	R	84	6	31.4	Opus2
P12	80	M	R	12	23	38.6	Opus2
P13	40	M	R	40	18	33.6	Opus2
P14	48	M	R	24	27	33.6	Opus2
P15	18	F	R	24	36	28.6	Opus2

Table 2

Individual speech perception findings

ID	EAR	SRQ (%)	SNR + 10 (%)	SNR + 5 (%)	STARR (dB)	SI-LPF (Hz)
P1	E1	60	10	0	74.3	220
P2	E2	50	0	0	46.3	220
P3	E3	80	40	0	15.1	27.5
P4	E4	100	50	20	3.6	34.5
P5	E5	100	60	50	2.3	27.5

ID	EAR	SRQ (%)	SNR + 10 (%)	SNR + 5 (%)	STARR (dB)	SI-LPF (Hz)
	E6	100	20	20	5.3	38
P6	E7	80	60	20	5.2	59
P7	E8	90	20	0	6.8	220
P8	E9	80	50	10	69.8	220
P9	E10	80	40	30	6.3	52
	E11	100	50	30	0.5	220
P10	E12	80	0	0	13.8	71
P11	E13	70	30	30	16.3	220
P12	E14	80	0	0	32.3	220
P13	E15	90	80	50	25.3	220
P14	E16	70	30	10	29.1	220
P15	E17	100	50	30	16.8	220
Q25 Q25		75	15	0	5.3	45
Median Median		80	40	20	15.1	220
Q75 Q75		100	50	30	30.7	220

Procedure

All testing was performed in a standard sound-proofed booth. Prior to testing, the participants were asked to set their processor to a comfortable listening level. For bilateral listeners, pitch and speech perception were tested ear by ear. The pitch and speech stimuli were presented via an Acer P253-MG computer (Hscinchu City, Taiwan) and a Sony TA-FE 320R preamplifier (Tokyo, Japan) connected directly to a single Tangent EVO E5 loudspeaker (Herning, Denmark) located at 0° azimuth and at 1 m distance from the participant's head. The order of testing was similar across participants: speech perception testing was followed by pitch perception. Between tests, short pauses were given whenever needed, and a test session was almost always completed within 1 h.

The SI-LPF test

For the evaluation of LF pitch perception performance, the SI test was performed in the LPF mode. In this mode, each sentence stimulus was low-pass filtered to remove high-frequency cues (MATLAB Filter Function: 300 Hz cut-off frequency, 90 dB attenuation in magnitude over a 50 Hz transition width) and high-pass-filtered white noise was added (250 Hz cut-off frequency, 85 dB gain in magnitude over a 50 Hz transition width) [12, 13].

The SI-LPF stimuli were based on pseudo sentences that were selected from an inventory of over 30.000 syllables consisting of frequently occurring phonemes in Italian, Romanian and Dutch languages. The recordings were made with a female speaker (F0 of 200 Hz) onto the computer (44.1 kHz, 16 bits) using a Sennheiser MKH 416 T directional condenser microphone. Each sentence was modeled by a sequence of four to six syllables (/mi, ma, mu, ni, na, nu/). A fixed pitch accent was imposed on the second syllable to have at least one pitch accent per sentence in addition to the boundary tone and to mimic a typical sentence-like structure. A variable-sized rise in F0 was imposed on the last syllable to address the perception of clause typing [12, 13].

The SI-LPF test consisted of an adaptive two-alternative forced-choice task with two consecutive sentences presented with an inter-stimulus interval of 500 ms. One sentence had a final rise, whilst the other one was either exactly the same or different, that is, without a final rise (a flat ending that remained at 200 Hz). The sentences were presented at 70 dB SPL and the listeners were asked to discriminate between same or different. A training module was used to familiarize the participants with both the stimuli and the task. The duration of training never exceeded 10 min. During the test phase, an adaptive one up-one down procedure was used to converge to the smallest ΔF_0 that the participant could discriminate (Just Noticeable Difference-JND). The rise in ΔF_0 ranged between a minimum ΔF of 0 Hz and a maximum ΔF of 208 Hz. The initial ΔF was set to 75 Hz. The ΔF changed following the listener's response, i.e. increased if the listener failed to discriminate or decreased after discrimination of the stimuli until estimating the 50% point on a participant's psychometric curve. When 100 trials were exceeded, the JND was presumed to be not present and JND was set above the maximum ΔF_0 value to 220 Hz. Presentations at ΔF of 0 Hz were included as internal controls and served to check if the listener misunderstood the task. The participants received feedback only for a false positive response. In such a case, an alarm sound was played to encourage them to report the presence of an intonation change only when it was reliably detected. When at least ten responses were recorded at this ΔF and

more than four of them were false positive responses, the procedure was aborted [12, 13].

Speech perception

Speech recognition in quiet (SRQ) as well as speech recognition using a fixed SNR method were assessed with sentences from the standard speech perception test developed by Cutugno et al. [21] for an adult Italian-speaking population. SRQ was tested with sentences presented at 65 dB SPL, whilst the performance in noise was evaluated with speech-shaped noise fixed at 65 dB SPL and sentences presented at + 10 and + 5 dB SNR (SNR + 10 and SNR + 5).

The Italian STARR test

Speech recognition based on a roving-level adaptive SNR method was assessed using the Italian STARR test developed by Dincer D'Alessandro et al. [16]. The test consisted of 10 lists, each containing 15 everyday sentences introduced by Cutugno et al. [21]. The sentences were presented at three presentation levels (at 50, 65, and 80 dB SPL) in a fluctuating speech-shaped noise to estimate an SRT, i.e. the SNR at which the listener achieved a 50% correct level [16].

The STARR testing started after explaining the task to participants. They were asked to repeat the sentence as accurately as they could. For each listener, a practice list was administered before a test list. The initial SNR was + 20 dB and varied adaptively following the participant's response. For scoring, single key words were highlighted in white on the screen, becoming green to indicate words repeated correctly. The clinician could either click on, the single key words repeated correctly or, alternatively, select the "all" or "none" options to indicate listener's response. The sentence where at least two out of three key words were correctly recognized was considered correct and the SNR for the following sentence was made more adverse. If insufficient key words were correctly recognized, the SNR for the following sentence became more favorable. The SNR step size started at 10 dB; dropped to 5 dB after the first reversal of the adaptive track and dropped again to 2.5 dB after a further reversal. The SNR was varied by adjusting the noise level, while presenting the speech at 50, 65, or 80 dB SPL as required; hence the SNR and required sentence presentation level let the software calculate and present the required noise level. The same SNR was used for all three speech levels (low, medium, and high levels). The SRT for each test list was computed by averaging the SNRs for the last nine sentences together with the SNR at which a next sentence would have been presented [16, 17, 18].

Statistical analysis

Data analysis was performed using Statistical Package for Social Sciences (SPSS) version 25.0 (Chicago, IL, USA). Non-parametric statistical tests were carried out for analysis since a Shapiro–Wilk test indicated that the data were not normally distributed for the SI-LPF ($p < 0.001$), for the STARR ($p = 0.003$), and for the SNR + 5 ($p = 0.005$). Data distribution was normal for the SRQ ($p = 0.056$) and for the SNR + 10 ($p = 0.363$). Spearman rank-order correlations were used to investigate the associations between pitch and speech perception performance. Additionally, the effects of demographic factors and aided pure tone thresholds were examined for SI-LPF and speech perception outcomes. The cut-off level for statistical significance was set to 0.05.

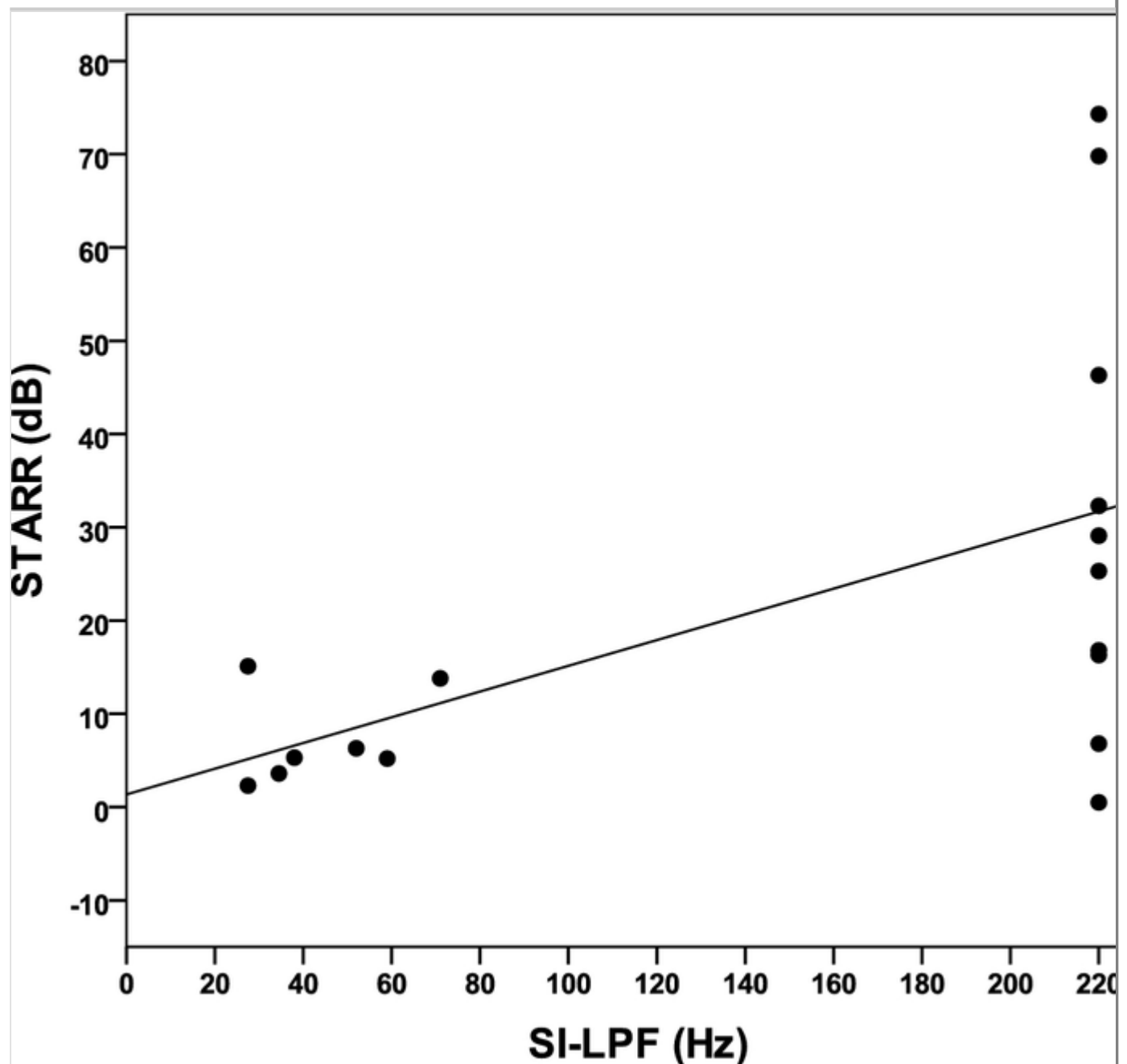
Results

Median SI-LPF and STARR scores were 220.0 Hz (range 27.5–220.0 Hz) and 15.1 dB (range 0.5–74.3 dB), respectively. Median SRQ was 80% (range 50–100%), whilst median fixed SNR scores were 40% (range 0–80%) for + 10 dB and 20% (range 0–50%) for + 5 dB, respectively. The individual speech perception outcomes as well as median values and percentiles (Q25 and Q75) are reported in Table 1.

SI-LPF findings showed significant positive correlations with STARR performance ($r_s = 0.63$, $p = 0.007$) whilst the associations with SRQ ($r_s = -0.37$, $p = 0.149$), SNR + 10 ($r_s = -0.24$, $p = 0.345$), and SNR + 5 ($r_s = -0.14$, $p = 0.587$) were not statistically significant. SI-LPF findings in relation to those obtained from the STARR test are represented in Fig. 1.

Fig. 1

SI-LPF findings in relation to those obtained from the STARR test. JND, Just Noticeable Difference



Demographic factors (age, duration of profound deafness before implantation, and duration of CI experience) and aided pure tone thresholds did not reveal any statistically significant correlations with SI-LPF and speech perception performance ($p > 0.05$).

Discussion

Perceptual ability to track changes in pitch helps a listener to disambiguate syntactic or semantic contexts such as clause typing usually marked by intonation changes in many languages like Italian [12, 13]. Pitch is also believed to play an important role to distinguish speakers and to focus on target speech in the presence

of various speakers or competing noise [13, 22]. Commercially available CIs have a reduced capacity to convey pitch information especially in the LF domain, partly due to their poor TFS processing [3, 4, 7, 8]. Indeed, CI listeners, in comparison to NH people, receive degraded LF pitch cues that might be fundamental for auditory perception especially when listening in everyday communicative situations where they typically face various speakers with differences in speech level in a fluctuating background [3, 7, 11].

Pitch perception is usually assessed using non-speech tasks such as discrimination of tone changes. However, the auditory processing of speech versus non-speech stimuli may differ and speech stimuli may put higher demands on attention and auditory memory. Hence, pitch assessment in linguistically relevant constructions may better reflect its effects on realistic listening situations [12, 13]. Recently, the A&E test suite offers a set of psychoacoustic modules for perceptual assessment of intonation changes cued by LF pitch. These modules include the SI test and the word stress pattern (WSP) test based on linguistic stimuli as well as the harmonic intonation (HI) and disharmonic intonation (DI) tests based on purely synthetic stimuli. For people with normal hearing or hearing impairment, findings reveal poorer performance on the linguistic tests than on the synthetic discrimination tests based on harmonic (a frequency sweep at F0 of 200 Hz together with its three harmonics) or inharmonic pitch glides (a frequency sweep at F0 only) [12, 13]. The present results show the same trend, especially in comparison to the HI test where HF cues are available in the non-speech stimuli. Such outcomes from CI listeners are consistent with those reported by Schauwers et al. [12]. More than 75% of the CI listeners obtain abnormal SI-LPF scores (higher than 50 Hz as reported by Heeren et al. [13]). The vast majority of CI listeners are unable to perform this intonational test and to perceive even the largest difference limen of 208 Hz, reflecting the CI users' inability to make use of TFS cues or to infer LF pitch information from these cues. Surprisingly, some listeners achieve scores within the normative range but reasons for such a good performance remain to be studied.

The present speech perception findings from postlingual CI listeners are consistent with results from previous scientific studies [18, 23, 24, 25]. The majority of the present sample (almost 80%) obtains a score of 80% or above on open-set sentences presented in quiet. However, their performance decreases dramatically when listening in the presence of noise, especially as the SNR becomes more adverse. Better performers from the group (approximately 40%) obtain a score of 50% or above for testing with the SNR fixed at + 10 dB, whilst several CI listeners show floor effects for testing with the SNR fixed at + 5 dB. Likewise, STARR findings

reveal abnormal SRTs in comparison to NH people. Although the majority of the group obtains scores less than 30 dB and shows the ability to understand speech in the presence of noise, no participant is able to achieve SRTs as well as NH listeners (SRT range from -5.8 to -9.7 dB SNR). On the other hand, very high STARR outcomes from poorer performers indicate their inability to understand speech even in quiet, since practically there is no detectable noise present especially for sentences presented at low level [16, 17, 18].

A close look at the individual data allows us to observe that the participants with a good SI-LPF score are only those who demonstrate a very good performance for listening in quiet (SRQs of 80% or above), but the SI-LPF associations are not statistically significant with speech perception tests neither for listening in quiet nor for listening in steady state noise. As expected, the SI-LPF findings are significantly correlated with the STARR performance. Despite limitations with respect to sample size, the strength of correlations between SI-LPF and STARR performance is very similar to that obtained using the WSP-LPF test which assesses listeners' perception of lexical stress by changes in LF pitch (correlation coefficient 0.60) [11], whilst it is considerably stronger than those obtained using A&E synthetic tests (correlation coefficient 0.44 for the HI and 0.22 for the DI) [7]. Such results strengthen the argument that the use of linguistically relevant contexts may better reflect the effects of pitch in communicatively realistic situations, more specifically when listening in challenging everyday situations where CI users listen typically to speakers with varying levels in a fluctuating background [11, 12, 13]. On the other hand, CI listeners who are unable to perform the SI-LPF test show a considerable inter-subject variability in STARR performance. Correlations with demographics and audiological outcomes do not reveal any significant predictor for such a difference in STARR performance. Nevertheless, the small sample size might have resulted in such findings. Indeed, a previous study by Dincer D'Alessandro et al. [7] shows significant effects of duration of deafness and aided pure tone thresholds on STARR performance in a larger Italian CI population. Similarly, Boyle et al. [17] report significant effects of CI thresholds on STARR performance.

The development and the use of new clinical assessment tools for pitch and speech perception in communicatively realistic situations may provide useful information to track improvements in longitudinal patient performance and in CI technology. Such findings may give us clues about CI recipients' improvements for daily communication skills and quality of life. Further studies in larger CI populations may specifically investigate the trend in better SI-LPF performers towards better

speech perception with roving-level adaptive test method. On the other hand, pitch perception findings on the linguistic tests and STARR performance in bimodal or bilateral CI users remain to be investigated, but ongoing studies in bimodal listeners indicate significantly better performance for both tasks [7, 10, 26, 27].

Conclusions

CIs have a reduced capacity to convey pitch information especially in the LF domain, partly due to their poor TFS processing which is known to play an important role to focus on target speech in the presence of fluctuating background noise. Pitch perception is usually assessed using non-speech tasks such as discrimination of tone changes. However, the auditory processing of speech versus non-speech stimuli may differ and pitch perception assessment in linguistic contexts such as clause typing marked by intonation changes may better reflect its role in communicatively realistic situations. Present findings reflecting considerably stronger correlations than those obtained using synthetic discrimination tests, and only for speech perception with roving-level adaptive test method support such an argument, and highlight in particular the effects of LF pitch perception and TFS sensitivity on challenging everyday situations, where CI users listen to speakers with varying levels in a fluctuating background. The development and the use of new clinical assessment tools for pitch and speech perception in communicatively realistic situations may provide useful information to track improvements in longitudinal patient performance and in CI technology. The findings may give us clues about CI recipients' improvements for daily communication skills and quality of life.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Ethical approval was obtained by the Local Ethical Committee. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Written consent was taken from all participants included in the study.

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