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Assistive listening technology in cochlear implant users in reverberant environments with multiple noise sources

Tecnologia auditiva assistiva em usuários de implante coclear em ambientes reverberantes com múltiplas fontes de ruído

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ABSTRACT

Purpose: This study aimed to evaluate the contribution of assistive listening technology with wireless connectivity in cochlear implant (CI) users in reverberating and noise situations. **Methods:** Prospective cross-sectional study approved by the Institutional Ethics Committee (CAAE 8 3031418.4.0000.0068). Adolescents and adults CI users with pre- or post-lingual deafness were selected. For bilateral users, each ear was assessed separately. Speech recognition was assessed using recorded lists of disyllabic words presented at 65 dBA at 0° azimuth with and without the Wireless Mini Microphone 2 (Cochlear™) connected to the Nucleus®6 speech processor. Room reverberation was measured as 550 ms. To assess the contribution of the assistive listening device (ALD) in a reverberating environment, speech recognition was assessed in quiet. To assess the contribution of the ALD in reverberation and noise, speech recognition was presented at 0° azimuth along with the noise coming from 8 loudspeakers symmetrically arranged 2 meters away from the center with multi-talker babble noise using signal to noise ratio of +10dB. To avoid learning bias or fatigue, the order of the tests was randomized. Comparison of means was analyzed by t test for paired samples, adopting significance level of $p < 0.005$. **Results:** Seventeen patients with a mean age of 40 years were invited and agreed to participate, with 2 bilateral participants, totaling 19 ears assessed. There was a significant positive contribution from the Mini Mic2 in reverberation, and noise+reverberation ($p < 0.001$). **Conclusion:** ALD was able to improve speech recognition of CI users in both reverberation and noisy situations.

Keywords: Hearing loss; Cochlear implantation; Speech perception; Assistive technology; Reverberation; Room acoustics; Noise

RESUMO

Objetivo: Avaliar a contribuição da tecnologia de escuta assistida em usuários de implante coclear (IC) em situações de reverberação e ruído. **Métodos:** Estudo transversal prospectivo aprovado pelo Comitê de Ética Institucional (CAAE 8 3031418.4.0000.0068). Foram selecionados adolescentes e adultos usuários de IC com surdez pré ou pós-lingual. Para usuários bilaterais, cada orelha foi avaliada separadamente. O reconhecimento de fala foi avaliado por meio de listas gravadas de palavras dissílabas apresentadas a 65 dBA a 0° azimute com e sem o Mini Microfone2 (Cochlear™) conectado ao processador de fala Nucleus®6. A reverberação da sala foi medida como 550 ms. Para avaliar a contribuição do dispositivo de escuta assistida (DEA) em ambiente reverberante, o reconhecimento de fala foi avaliado no silêncio. Para avaliar a contribuição do DEA em reverberação e ruído, o reconhecimento de fala foi apresentado a 0° azimute com o ruído proveniente de 8 alto-falantes dispostos simetricamente a 2 metros de distância do centro com ruído de múltiplos falantes usando relação sinal-ruído de +10dB. Para evitar viés de aprendizado ou fadiga, a ordem dos testes foi randomizada. A comparação das médias foi analisada pelo teste t para amostras pareadas, adotando-se nível de significância de $p<0,005$. **Resultados:** Dezessete pacientes com idade média de 40 anos foram convidados e concordaram em participar, sendo 2 participantes bilaterais, totalizando 19 orelhas. Houve contribuição positiva significante do Mini Mic2 na reverberação e ruído+reverberação ($p<0,001$). **Conclusão:** DEA foi capaz de melhorar o reconhecimento de fala de usuários de IC tanto em situações de reverberação quanto ruidosas.

Palavras-chave: Surdez; Implante coclear; Reconhecimento de fala; Tecnologia assistiva; Reverberação; Acústica dos ambientes; Ruído

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INTRODUCTION

Hearing impairment is a significant and prevalent problem in the population, which affects the patient's personality and social life, and can cause isolation and reclusion[1].

Cochlear implant (CI) is currently the treatment of choice for severe to profound deafness. In properly selected patients, the CI makes good hearing possible, facilitating general communication and normal language development in children with congenital deafness[2-5].

Although the cochlear implant offers the opportunity for speech recognition in silence, however, in complex acoustic environments and in the real world, speech understanding remains a challenge[6-10]. In these situations, the presence of reverberation and background noise can cause significant deterioration in the understanding of a conversation.

The literature has also studied the challenges faced by individuals with hearing loss in reverberation situations both in hearing aid and in CI users[10,11].

Reverberation is a common source of everyday acoustic degradation. It refers to sound that persists in a space by continuing reflection against the characteristics of the environment, even after the sound source ends. These continuous reflections, produced by early (or direct) and late reflections, degrade the transmission of speech information by distorting spectral and temporal information, both at phonemic and word levels[10]. Late reflections tend to fill in gaps in the temporal envelope of speech and reduce low-frequency envelope modulations, which are important for speech intelligibility.

Unlike reverberation, noise masks weaker energy consonants to a greater degree than higher acoustic energy vowels. A research[9] concluded that the combined effects of reverberation and noise are more harmful to speech intelligibility than reverberation-only or noise-only effects.

In recent years, the use of wireless remote microphone systems is proposed to improve hearing in challenging listening situations[12]. These systems consist of a microphone located close to the speaker's lips, which captures the speech sound to transform it into an electrical wave and transmit the signal directly to a receiver at the user´s hearing device through a digital transmission of radio frequency (RF) similar to frequency modulated (FM) systems. By capturing the signal at or near the source, the signal to noise ratio (SNR) at the listener's ear is increased and consequently the negative effects of ambient noise, as well as those of distance and reverberation will be reduced[13-15].

Remote microphones for wireless connectivity based on the 2.4 GHz frequency band, may offer clearer and more stable signal transmission, since lower frequencies can more easily penetrate solid objects[16]. GN Resound group shared the technology with Cochlear Ltd. in a partnership called Smart Hearing Alliance. This equipment is compatible with sound processors for both implantable hearing aids and cochlear implants. The literature[12] found a significant increase in speech recognition in silence and in noise, both for unilateral and bilateral CI users, whenever the wireless connectivity microphone was used.

Although the literature has already investigated the influence of noise and reverberation in CI users in challenging auditory simulated environments and the contribution of assistive technologies, this study aimed to assess whether there is a contribution of wireless connectivity systems to speech recognition in situations of natural reverberation and in noise with multiple sources in cochlear implant users.

METHODS

This prospective cross-sectional study was approved by the Institution Ethics Committee for the Analysis of Research Projects under protocol number CAAE.83031418400000068.

Adolescents or adults with severe to profound pre- or post-lingual deafness who received cochlear implants at our CI Group were selected and invited to participate after signing the free and informed consent form. Inclusion criteria included Nucleus system users (Cochlear Ltd., Australia) with speech recognition equal or better than 50% in silence regardless of the time of cochlear implant use. Individuals who had declared or diagnosed cognitive difficulties or mobility difficulties that prevented the collaboration with procedures involved in the study excluded from the sample.

To ensure the homogeneity of the assessment and safety in the operation, the same Nucleus 6® speech processor (CP910), compatible with the MM2 (Mini Mic 2®), was used for the research, regardless of the processor used by the patient. Likewise, to ensure stable and proper operation, the same MM2 device connected via 2.4 GHz to the CP 910 processor was used in all evaluations. Despite the evaluations being performed with the specific research processor, all maps with the settings and programming parameters in use by the patient were kept, converted and transferred from their processor to the research processor. The mixing ratio between the MM2 and the processor microphone was maintained at 2:1 for all patients. The 2:1 mixing ratio prioritizes the input of the MM2, reducing the audibility of the sounds that enter directly through the microphone of the CP910 Processor, in a ratio of 60% through the MM2 and 40% through the microphone of the processor. Speech processor and MM2 volume was maintained for all assessments.

Speech recognition in silence and in noise was investigated in adults with pre- or post-lingual deafness, unilateral or bilateral cochlear implant users with and without the use of the Mini Mic 2® Cochlear™ wireless assistive technology remote microphone (Sydney, Australia) positioned at 20 cm from the speaker (Figure 1). Four different recorded lists of 25 psychometrically balanced disyllabic words presented by male voice were used[17].

Dimensions of the test room were 3,70 m x 3,98 m long x 2,10 m high. The background noise level in the room was 31 dB LeqA (Chart 1).

To verify the contribution of the device in an environment with reverberation, speech recognition was evaluated in silence with and without the wireless connectivity device (Mini Mic®), in a quiet room with reverberation (RT60) measured to be 419 ms for words spoken by a male voice and 429 ms as average for speech materials with speech coming from the front and the assistive listening device positioned at 20 cm from the speaker (Figure 1).

To verify the contribution of the MM2 in noise and reverberation, speech recognition was assessed presenting speech coming from the front and multi-talker babble noise of seven sources separated by 45º with signal-to-noise ratio (SNR) of + 10dB, and speech presented at 65dB SPL. To avoid learning bias or fatigue during the assessment, test order was randomized through the website Research Randomizer[18].

Chart 1. Test environment: room dimensions (Binaural Auditory Skills Laboratory - LHAB)

Room dimensions	Width: 3.70 m x Length: 3.98 m x Height: 2.10 m
System Data	Computer: 2x2.4GHz 6-Core intel processor, Xeon; Memory 12GB, 1333MHz DDR3. 3.2; Operating system: Apple OSX version 10.8.5. 3.3; Application (audio control): Reaper, v4.52/64 rev 749c96. sep 5 2013. 3.4
	Audio Interface: M-Audio Pro Fire 610, 24 Bit/192 kHz (NS: 20RR51431066); M-Audio Pro Fire 2626, 24 Bit/192 kHz (NS: 204A150C23653)
Noise parameters	8 speakers evenly distributed in the horizontal plane with an angular distance of 45° positioned from the patient: 1.20m
	noise level at the center of the room: 31.1, 39.8, 28.6 dB
	Reverberation measured at 0o azimuth, for male-voiced speech material at 70.4 dB at 312 ms for T30 and 419 for T60.

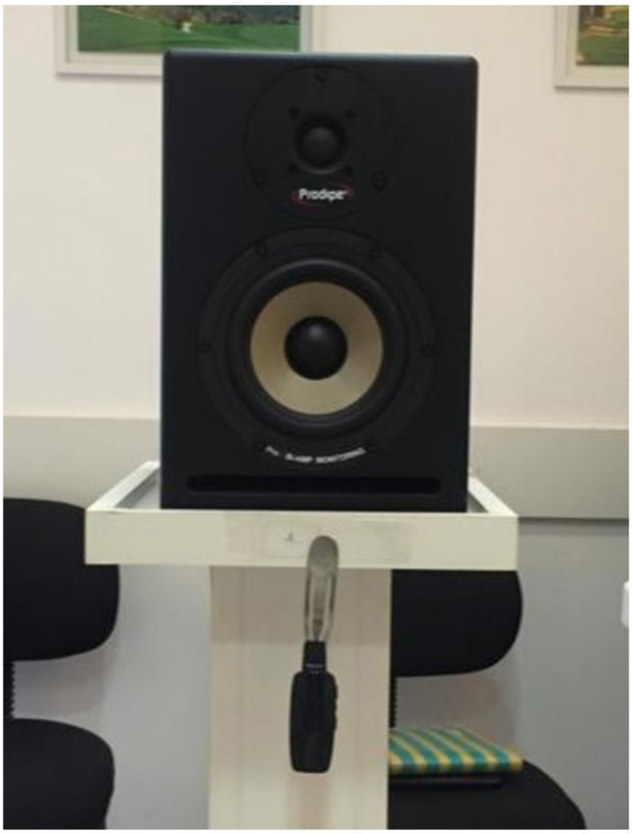

Figure 1. Position of the microphone at 20 cm from the speaker

Table 1. Demographic data of the studied sample

N	17
Age (in years) (min – max)	40.75 (17 – 54)
Gender	
Female	9
Male	8
Time of use of the CI (in months)	12 (7 – 16)
Side	
Left	10
Right	7
Etiology of deafness (N)	
Meningitis	1
Unknown	9
Otoxicicity	1
Infectious (not meningitis)	2
Trauma	3
Autoimmune	1
Internal device	
CI N22	1
CI N24	6
CI 24RE	7
CI 422	3
Speech processor in use	
CP 810	6
CP 802	9
CP 910	2

Percentage of correct answers of speech recognition in reverberating and in reverberation + noise situations, without and with the use of the wireless connectivity system (Mini Mic) were compared using Wilcoxon signed rank test.

RESULTS

Seventeen patients with a mean age of 40 years, ranging from 17 to 54 years of age, were selected, and agreed to participate in the research, 2 of them with bilateral CI. Of the patients evaluated, 9 were female and 8 were male, users of all Cochlear™ internal devices CI N22, CI N 24, CI 24RE, CI 422 and speech processors CP 802, CP 810 and CP 910. The etiologies found in the study participants were meningitis, autoimmune, trauma, ototoxicity and patients with unknown etiology (Table 1). The final analysis included 19 assessments, including both test situations (silence and noise with and without MM2).

Tables 2 and 3 present the results of speech recognition in the test situations in silence (in an environment with reverberation time measured at 535 ms for azimuth 0) and in noise. There was a significant positive contribution of the Mini Mic in both situations, silence and noise.

Patients recruited based on the inclusion criterion of 50% sentence recognition in open booth presentation, when evaluated in the Binaural Auditory Skills Laboratory, showed great difficulty in speech recognition in a silent situation (Lhab background noise = 31 .1 dB LeqA) with reverberation only, showing an average performance of 35% without MM2.

There was a contribution of the MM2 to the improvement of speech recognition in isolated reverberation situations, increasing the performance from 35% to 49% on average (Table 2). The contribution of the MM2 to the improvement of speech recognition in situations of reverberation associated with noise was also observed, increasing the performance from 26% to 52% on average (Table 3).

Figure 2 shows the performance variation of the participants; however, all showed a contribution from the use of MM, both in isolated reverberation situations and associated with noise.

Figure 3 shows the difference between the performances with and without MM in both test situations, revealing that the MM contribution was greater for situations of reverberation associated with noise.

Table 2. Contribution of wireless connectivity systems (MM2) to speech recognition (%) in isolated reverberation situations compared by Wilcoxon test

	Silence without MM2	Silence with MM2	p
N	19	19	
Mean	34.73	50.76	0.0002
Standard deviation	17.9	18.5	
Standard Error	4.1	4.2	
Confidence interval (95%)	-21.5285 to -10.4715		

Subtitle: MM2 = Mini microphone

Table 3. Contribution of wireless connectivity systems (MM2) to speech recognition (%) in noise and reverberation (R) situations compared by Wilcoxon test

	Noise + R without MM2	Noise + R with MM2	p
N	19	19	
Average	25.89	51.79	0.0001
Standard Deviation	15.90	20.76	
Standard Error	3.50	4.10	
Confidence interval (95%)	-33.9824 to -17.8071		

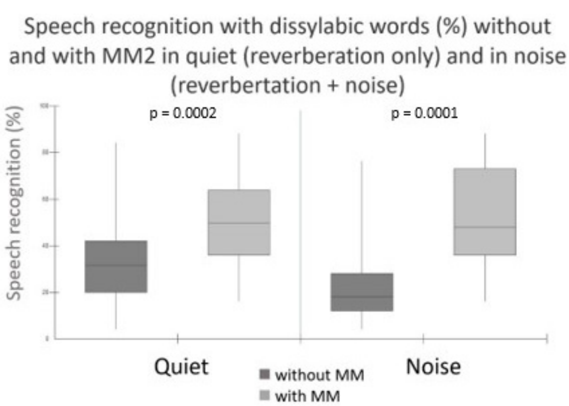

Figure 2. Box plot of the speech recognition (%) with and without Mini Mic2 in silence with reverberation only, and in noise with reverberation

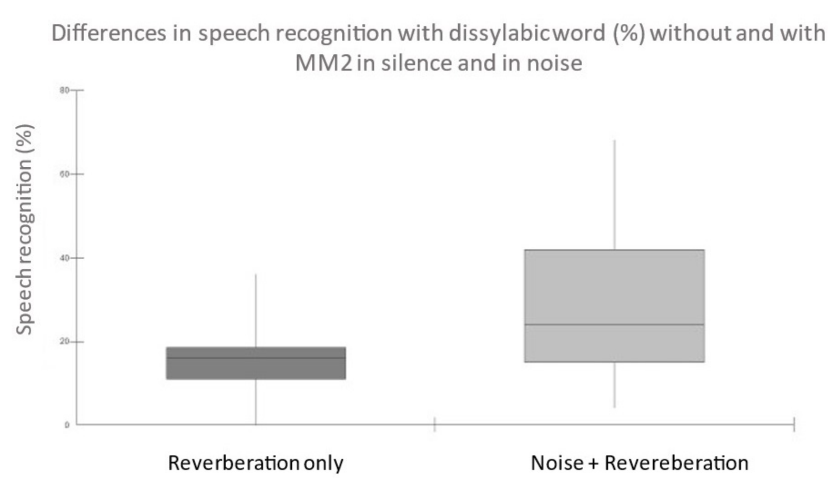

Figure 3. Difference between the recognition of disyllables with and without MINI MIC2 (in %) in silence and in noise

DISCUSSION

The cochlear implant is an extraordinary device that offers the opportunity to hear for those who cannot benefit from conventional hearing aids. However, it still does not mirror the properties of the entire natural auditory system. The cochlear implant replaces the function of sensory cells in triggering the auditory nerve impulse, however, the other functions of the peripheral auditory system should be equally represented. Some features of the speech processor are intended to imitate natural events that happen in normal listeners, such as the contribution of the pinna, the middle ear muscles in the focus of attention and in the separation of background noise. Likewise, the controlling role of outer hair cells and the olivo-cochlear system apparently so effective in individuals with normal hearing could not yet be represented in the cochlear implant signal[19]. Therefore, external resources such as those offered by assistive hearing technologies are necessary and important.

Research has demonstrated the difficulties presented by CI users in a noisy and reverberant environment[7,11,20]. Several studies showed considerable improvement in speech recognition in noise in CI users using assistive hearing technologies in adults and school-age children, but the contribution in natural reverberant environments has not yet been explored[12,15,16,21,22]. The characteristics of the noise level and reverberation information reported in the current study are in line to design an ecologically-valid assessment.

The present study identified the great difficulty of cochlear implant users in a reverberant situation, considering that, according to the sample selection criterion, they had 50% or more of sentence recognition in an open presentation in a soundproof booth. In the silent situation of the room with 419 ms of reverberation for sounds presented in the box at 0o azimuth with words emitted by a male voice, the average performance was 35% without MM. This fact confirms the report by the literature[23] that classical audiological assessment generally includes measures of speech intelligibility, using material with recording of only one speaker and fixed noise in controlled environments, in the laboratory or clinic, but does not consider the complexity of human communication in real and dynamic contexts. In fact, one research[9] studied the effect of the coexistence of noise and simulated reverberation on the intelligibility of 11 adult implants and observed that the intelligibility dropped from 87.36% (silent situation) to 44.16% and 32.94% in the two reverberation situations: T60 = 0.6 s and T60 = 0.8 s respectively. Adding noise to the reverberation results showed even greater deterioration, decreasing speech recognition by almost 80%. Similarly, another research[20] used speech stimuli corrupted by both early reflections and late reflections to investigate the effects on speech intelligibility in cochlear implant users. The average speech intelligibility performance dropped from 90% in the anechoic condition to about 70% for RT60 = 0.3 s in the reverberant condition. In the afterthought condition, CI users scored approximately 60% lower than in the anechoic condition.

The present study demonstrated a significant positive contribution of the Mini Mic 2 in both situations, isolated reverberation (silence) and noise associated with reverberation.

The Lhab noise situation, represented by the babble noise coming from 7 speakers arranged around the patient, exposes a great hearing challenge, with most studies presenting 2, 3 or 4 noise sources[12,21,24-26]. In this situation was the greatest contribution presented by assistive technology, considering that the MM2 was 20 cm from the box exit presenting the target words of the test. Both in an environment where the reverberation is controlled and in a natural reverberant environment, we can observe a significant deterioration in the speech recognition of individuals using CI.

A group of researchers in the Netherlands[16] evaluated the benefits of a wireless remote microphone in bimodal cochlear implant users in 13 adults with post-lingual deafness in a soundproof booth. A difference in the speech recognition threshold in noise of 5.4dB was found between the use of the CI with MM and without the MM, and an additional improvement in the speech recognition threshold in noise of 2.2dB with bimodal stimulation paired to the MM.

The literature[11] investigated the impact of reverberation and source-receiver distance on speech intelligibility in quiet environments, in cochlear implant users, in a variety of listening scenarios. The authors evaluated the effects of early and late reflections on IC intelligibility, using both reverberation time variations and source distance. Seven adults with post-lingual installation deafness participated in this study conducted using virtual reverberation systems reproducing 3 environments with different reverberation times between 0.3 and 1.7 s, and distance between source and participant of 1 meter, 3 and 6 meters. Furthermore, it was confirmed that CI users were largely impacted by the source-receiver distance: when the speaker was simulated as being 1m away, good intelligibility was maintained even in rooms with very high reverberation times (TR = 1.7 s). However, when the speaker was simulated as being 3 m away, the evaluated individuals showed good intelligibility only in rooms with moderate reverberation times (TR between 0.3 and 0.5 s).

The literature also[27] investigated the relationship between several variables that can influence speech intelligibility at different levels of reverberation, covering the degree of hearing loss, age, temporal processing and working memory capacity. Thirty-three elderly people between 59 and 88 years of age with symmetrical sensorineural hearing loss of varying degrees participated in the study. Temporal processing was measured by the threshold of gap detection from 20 ms. Three virtually simulated reverb variations were used, no reverb (0.0 s), moderate reverb (1.0 s), and severe reverb (4.0 s). The dimensions of the acoustically isolated room were fixed at 5.7 m × 4.3 m × 2.6 m, and the distance from the source to the participant was 1.4 m to represent a typical conversational distance. In the no-reverberation condition, temporal gap detection was the only factor associated with speech recognition. When speech was degraded by moderate reverberation (1 s), both age and degree of hearing loss were associated with speech recognition. Working memory and age were both statistically associated with speech recognition under intense reverberation conditions (4 s). These variables indicate that speech intelligibility can be substantially affected by reverberation, but individual characteristics influence it differently depending on the reverberation conditions.

The group of the Hearts for Hearing Foundation[12] conducted a study to evaluate speech recognition in silence and at increasing noise levels in CI users using only the Nucleus 6 sound processor versus the Nucleus 6 sound processor and Cochlear remote microphone (Mini Mic). Sixteen adults who had at least 50% of monosyllabic word recognition in silence participated in the study, using the Nucleus 6 speech processor (CP910), which has a 2.4 GHz antenna. The sound processor was set to an audio mix ratio of 1:1, which is the manufacturer's default setting for adults using the signal preprocessing strategy for noise reduction (auto-sensitivity) under all evaluation conditions. The sentence presentation level was 85 dBA at the Mini Mic Cochlear location and 65 dBA at the participant location. The noise was presented in six intensities: 50, 55, 60, 65, 70 and 75 dBA. The noise intensity was identical at the participant's location and at the Cochlear Mini Microphone. The evaluation was carried out in a 7.71m x 7.55m x 2.74m room with 44 dBA background noise. The sentences were presented by loudspeakers located 4 m from the participant, at 0o azimuth. The noise mimicking classroom noise was presented by four speakers located at approximately 30º, 135º, 225º and 330º azimuth in relation to the participant. Speech recognition in silence and at all noise levels except the 75 dBA condition was significantly better using the remote microphone compared to performance with the sound processor alone. Performance was significantly worse as the noise level increased. The use of the remote microphone provided superior speech recognition in silence and noise when compared to the performance obtained with the sound processor alone.

The literature[26] recognizing that CI users show difficulty in noise situations and may even present selective attention changes, compared the speech performance in noise situations in CI users using two types of wireless connectivity: the frequency system modulated (FM) with Roger Inspiro accessory with Euro receiver, and the Cochlear Wireless Mini Microphone (MM) accessory that uses 2.4 GHz transmission via an antenna built into the speech processor. Eleven adolescents with a mean age of 13 years were studied. Both systems improved performance in speech recognition, although the gain was greater with the MM system (SRT = 4.76 dB) than the Roger system (SRT or LRF = 3.01 dB). The use of assistive technology outweighed the benefits of the speech processor's noise reduction algorithm.

Another study[24] evaluated the effect of wireless remote microphones (MR) on speech-in-noise discrimination scores in CI users. Twenty children with unilateral cochlear implants with a mean age of CI users for at least one year were evaluated. Noise was assessed using the Words in Noise (PNR) test at a constant signal-to-noise ratio (SNR) of 0 dB, in the presence and absence of a wireless MR. Three loudspeakers were placed at a distance of 1 m in front of the child to present the speech stimulus. The average word discrimination score in noise in the absence of wireless MR in all children was 34% (6.8 words out of 20), with variation between 15% and 50%, while with the use of RM the average was 65% (13 words out of 20), ranging between 35% and 95%. The significant improvement observed in speech recognition in noise in all children with CI when the wireless MR was used, suggests the usefulness of this accessory in CI users and the indication of its use also in children.

Since the use of remote microphones help access clear speech, it has been reported to be useful even in toddlers and young children´s home environment, regardless we agree and accept to pay the price of adverse effect of diminished auditory experience on localization and figure-to-ground discrimination during auditory development[28,29].

Despite normal hearing individuals can tolerate environments with reverberation times greater than 1 second, literature have reported that performance for cochlear implant users decreases on reverberation situations beyond 0.3 seconds. Indeed, listening effort might not be impacted by reverberation in normal hearing adolescents and young adults[30], but it does in hearing impaired[31]. According to our results, assistive listening devices may decrease this impact for cochlear implant users.

CONCLUSION

Wireless connectivity systems significantly contribute to speech recognition not only in multi-source noise situations but also in reverberating environments in adult cochlear implant users.

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