Critical Review: What are the spatial and non-spatial benefits of bilateral compared to unilateral cochlear implants in adults?

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Spatial effects (or spatial unmasking) of binaural hearing include the head shadow effect and the squelch effect while the binaural summation effect for speech and music may be considered as non-spatial effects. This critical review examines how adults with two cochlear implants can benefit from the aforementioned effects when put in a noisy environment. This critical review examines four studies, which investigate the effect of bilateral cochlear implantation on the aforementioned effects. Study designs include three within group repeated measures, and a nonrandomized clinical trial. Localization abilities will not be specifically addressed in the scope of this paper. Results indicate that bilateral cochlear implant recipients have better speech perception in noise and music perception overall. Further explanations are explored and clinical implications and recommendations are included.

Introduction

Although adults receiving one cochlear implant perform well in terms of understanding speech in calm situations, they tend to have greater difficulty in understanding speech in the presence of background noise. It is argued that patients with bilateral cochlear implants have access to the head shadow effect, binaural squelch, and binaural summation effects, which results in greater improvement in speech recognition during noisy conditions (Ricketts et al, 2006). The head-shadow effect occurs when speech and noise arrive at the ears in different directions, respectively. For example, noise originating from the right side would affect the right ear but the head would obscure (thus creating an acoustic shadow) some of the noise from reaching the left ear. Thus, the head shadow effect would increase the signal to noise ratio (SNR) in the left ear (Brown and Balkany, 2007). This can be thought of as a monaural phenomenon that occurs primarily due to the speech and noise being spatially separated, and does not require any auditory integration of the two signals.

The binaural squelch effect also occurs when noise and speech are spatially separated resulting in two different inputs in both ears. However, the squelch effect requires central processing and auditory integration of both signals so that the auditory cortex receives a more unified and complete picture than could have been achieved with just listening using one ear alone (Brown and Balkany, 2007).

Binaural (or diotic) summation (also known as binaural redundancy) also requires central auditory processing, but in this condition, both ears share the same auditory input. As a result, the signals are combined and the brain perceives this as 3 dB louder compared to listening to the same signal with just one ear. This increase in loudness also leads to better intensity and frequency discrimination. In this manner, a patient having access to the binaural summation effect (through bilateral implantation) can demonstrate better speech intelligibility in both quiet and noisy conditions (Brown and Balkany, 2007).

In terms of music, cochlear implant recipients show poorer perception, even when the music is presented in quiet conditions. This can be explained by music having a more varying sound spectrum, consisting of a larger range of frequencies, and limited redundancy. All of these factors create greater limitations for listening using electrical means (Veekmans, Ressel, Mueller, Vischer, Brockmeier, 2009). Currently, there is limited research on the music perception of bilateral implant recipients. However, it is hypothesized that binaural hearing can also improve music perception overall.

Objectives

The primary objective of this paper is to critically evaluate the existing literature regarding the effectiveness of bilateral in comparison to unilateral implantation in providing access to the head shadow, binaural summation, and binaural squelch effect, as well as improving music perception in adults.

Methods

<u>Search Strategy</u>
Computerized databases including PubMed, MEDLINE, and PsycINFO were searched using the following search strategy: ((bilateral cochlear implant*) OR (bilateral implantation) AND (adult*) AND (head shadow) OR (squelch) OR (music perception) OR (binaural benefit)). The search was limited to articles written in English. Additional articles were obtained by examining the reference lists of relevant journal articles.

Selection Criteria

Studies selected for inclusion in this critical review were required to examine the effects of bilateral implantation on the head shadow, squelch, and binaural summation effects using challenging speech-perception tasks, speech recognition in the presence of different noise sources, and music perception tasks. Participants in the studies were adults with sensorineural hearing impairment or who were postlingually deafened. There were no restrictions on the demographics of the subjects or the outcome measures.

Data Collection

A review of the literature yielded four peer-reviewed journal articles. Three of four studies consisted of a within groups (repeated measures) design and the fourth study was a nonrandomized clinical trial with a mixed design. These studies also represented a diverse range of research groups that included adults who were postlingually deafened, those who were bilaterally implanted and were native speakers of American English, adult participants who received simultaneous implantation, participants who received sequential CIs, native German-speaking adults who received bilateral implants, unilateral implants, and normal-hearing listeners.

Results

Within Groups Repeated Measures

Ricketts, Grantham, Ashmead, Haynes, and Labadie (2006) conducted a study to compare speech recognition in noise for patients with two implants as opposed to one implant. They were also interested in how long the bilateral speech-recognition advantage would last, and how varying the signal-to-noise ratio (SNR) would influence the magnitude of the bilateral advantage. Participants included 16 adults, who were postlingually deafened and who received a MED-EL C40+ implant in both ears. The researchers examined both ears separately, and then both ears together 4 to 7 months after the initial activation using five spatially separated, varying noise sources in a fixed SNR condition of +10 dB and an adaptive-SNR condition. The Adaptive-SNR condition was used to reduce or eliminate ceiling and floor effects that frequently occur in fixed-SNR conditions. The dependent variable in an adaptive-SNR task as well as in a fixed-SNR task was speech recognition performance on The Hearing in Noise Test (HINT) and the Connected Speech Test (CST). The researchers hypothesized that the different SNR testing methods would have an effect on the magnitude of the bilateral advantage observed.

The Hearing in Noise Test (HINT) was modified to include different noise sources and served as the adaptive-SNR condition. The HINT measures speech recognition in noise when the noise occurs in the same ear as speech and when it is in the opposite ear as speech. The Connected Speech Test (CST) was used during the fixed-SNR task, whereby five uncorrelated noise samples are used instead of the standard single competing noise. Performance on the HINT and CST across test conditions (best unilateral ear and bilateral conditions) was analyzed separately using two single-factor repeated-measures analyses of variance (ANOVA). Statistical analysis on the HINT showed that participants had lower SRT scores when using both implants than when using the implant in the best ear with an average advantage of 3.3 dB. Similarly, the CST results also yielded an average advantage of 9% when listening with both implants. Thus, the primary dependent variable in this study was the 3.3-dB bilateral cochlear implant advantage, which is primarily attributable to the binaural effects of both binaural squelch (0.9 dB) and diotic summation (2.1 dB).

In a subsequent study, 10 of the original participants were re-tested using the same fixed-SNR task 12 to 17 months after activation of their implant to investigate how the patients' speech recognition might change over time while using both implants as opposed to one. All of the procedures used in this experiment remained the same. Results indicated that in addition to the bilateral advantage, 8 of the 10 participants performed significantly better due to greater experience with using their implant. The amount of the "experience advantage" ranged from 10 to 80% in these eight listeners. This advantage was calculated by subtracting the CST score at 4 to 7 months from the CST score at 12 to 17 months while listening with both implants as well as with one implant.

A limitation in this follow-up study was that the participants were not chosen randomly. Instead, the first 10 participants who volunteered and were able to return for retesting were chosen. As a result, the findings may not be generalizable to the public at large. Furthermore, because the participants were never evaluated in a condition where speech and noise originated from the same direction, the researchers could not state whether the bilateral advantage was due to binaural squelch or binaural summation. As a result, the bilateral advantage obtained in the current study may be due to summation effects that overrode the smaller contribution of squelch effects. In this study, most of the etiological factors behind the hearing loss were unknown and no mention was made on whether users' normal everyday program of their speech processor was used during the testing.

Within Groups Repeated Measures

Wackym, Runge-Samuelson, Firszt, Alkaf, and Burg (2007) investigated testing conditions that would result in a binaural benefit in seven adult cochlear implant recipients. They used tests that presented word and sentence stimuli in quiet and at three different noisy situations. They had seven adult bilateral implant participants and their speech-recognition performance was tested using their best-performing ear (either right or left), and using both ears together. HINT sentences, CNC words, and the Speech Perception in Noise (SPIN) were used as testing materials. The quiet condition consisted of HINT sentences presented at 60 dB SPL. The noisy condition consisted of the same sentences presented at 60 dB SPL with speech-weighted noise in the background at +8 signal-to-noise ratio. CNC words were also presented at both 50 and 60 dB SPL minus any noise and SPIN stimuli were introduced at 70 dB SPL in a background of a 12-person multi-talker babble at +8 signal-to-noise ratio. Subjects were positioned in front of a single speaker, which also delivered both the speech stimuli and noisy conditions to test the binaural summation effect

In general, participants showed the greatest performance for sentences presented in the 60 dB SPL quiet condition, followed by sentences presented at 60 dB SPL in the speech-weighted noise condition. Words delivered at 60 dB SPL proved to be more challenging than sentence stmuli presented at 60 dB SPL in both calm and noisy conditions. The most challenging speech-recognition test was the SPIN, since it uses multitalker speech babble as its noise source. In comparing the values for participants listening with one implant as opposed to two implants, their HINT values showed a -8 to +30% improvement, HINT values in noise ranged from +3 to +10%, CNC words presented at 60 dB SPL ranged from +6 to +20%, CNC words presented at 50 dB SPL ranged from -10 to +10%; and the SPIN test scores ranged from 0 to 22%. Overall, improvements could be seen in SRT scores in all participants and in all testing conditions. More importantly, as the testing conditions became more challenging, there were steady improvements in participants using both implants versus one implant in their preferred ear, especially when background noise was introduced, and when word stimuli were delivered at 60 dB SPL in quiet. The Abbreviated Profile of Hearing Aid Benefit (APHAB) was also administered to which all participants indicated at least 38% subjective benefit for each testing situation.

A limitation to this study is the small sample size used. For example, three of the seven participants received their implants at the same time and therefore, never had any experience with using a single implant. To this effect, the subjective assessment using the APHAB was between bilateral versus their listening prior to receiving an implant, instead of between bilateral and unilateral implant conditions. Due to the limited number of participants and variable scores, the researchers could not statistically analyze these results.

Within Groups Repeated Measures

Schleich, Nopp, and D'Haese (2004) conducted a study to investigate the head shadow effect, binaural squelch, and binaural summation effects in patients receiving the MED-EL COMBI 40/40+ cochlear implant by testing their speech perception in varying noise conditions.

The 21 participants were native German-speaking adults and ranged from 17.5 to 66.5 years old (mean of 44 years). The Oldenburg sentence test, which is an adaptive sentence test was presented at three difficult listening situations. The speech signal was played from a front speaker, while the noise source was delivered in one of three conditions: the front, left, or right side. For each of these conditions, participants were tested in the unilateral left, unilateral right, or bilateral condition. The noise signal was held constant at 60 dB SPL for all three conditions.

For each test, the speech input was altered in order to achieve 50% correct in the last 20 sentences that were presented. Therefore, SRT levels were calculated by taking an average of the speech input levels for the last 20 sentences and subtracting the 60 dB SPL noise signal. For the left-only and right-only conditions, the researchers calculated the amount of the head shadow effect by subtracting the unilateral SRT score obtained when the noise was presented at the opposite side of the implant used, from the SRT score obtained when both the noise and implant were on the same side. In this way, head shadow is defined as an improvement in SRT scores (lower scores) when the noise shifts from the same side of the implant to the opposite side whereby the noise is essentially blocked by the recipient's head.

To calculate the magnitude of the squelch effect, the SRT when using both implants was subtracted from the SRT when listening to the opposite implant. Therefore, the squelch effect provides an additional binaural benefit when the speech signal is spatially separated from the noise (i.e. when the speech is presented in a different direction than the noise). To calculate the magnitude of the binaural summation effect, the SRT when using both implants was subtracted from the SRT obtained when the speech and noise signal originated from the same direction (in the front). A positive effect on speech perception is inferred from a positive SRT value. In looking at the averages across the group of participants, the researchers found that the SRT scores were the best (i.e. lowest) when both implants were used for all three noise scenarios, whereby the head shadow effect provided an additional 6.8 dB benefit, the squelch effect provided 0.9 dB, and the binaural summation effect provided an extra 2.1 dB.

Nonrandomized clinical trial; mixed design

Veekmans, Ressel, Mueller, Vischer, and Brockmeier (2009) conducted a study to understand the music listening habits of 23 bilateral cochlear implant recipients using two control groups: 23 unilateral cochlear implant recipients and 23 participants with normal hearing.

The Munich Music Questionnaire (MUMU) was used to examine participants' music listening preferences and the degree of enjoyment obtained from listening to music. All of the cochlear implant users spoke German, lost their hearing after acquiring language, and had at least one year of experience with using their current implant. For the bilateral implant group, recipients completed the questionnaire after receiving their second implant. Therefore, this study constitutes a retrospective design. By contrast, the researchers mentioned that using a prospective design whereby the questionnaire is administered after receiving the first implant, instead of after the second implant would have been better since asking participants to remember their experience of using only one implant leads to biases in reporting. More specifically, the bilateral implant group might expect themselves to have a higher performance (i.e. give a higher score on the questionnaire) in order to justify their expenditures on the second implant.

The researchers analyzed their data by comparing the music experience of the bilateral group after receiving their second implant to their first implant (within-subject), by comparing both unilateral and bilateral recipients to participants with normal hearing (between-group), and by looking at the responses of bilateral recipients and comparing these to participant demographics using Spearman's correlation coefficient. A 5-level Likert scale was used to facilitate statistical analysis. The use of non-parametric statistics was appropriate for this study because the researchers were not making assumptions about the probability distributions of the music preferences of the bilateral group after receiving the second implant. Preferences are subjective (i.e. we cannot predict the type of distribution it would follow). Therefore, using this statistical method is valid. One-way analysis of variance (ANOVA) was performed to examine mean group values for normally distributed data.

For the within-group comparison, the music listening abilities of the bilateral group improved after receiving their second implant whereby the music sounded better to 95.5% of the group, sounded more natural to 90% of the recipients, and sounded more pleasant to 85% of the group. The researchers also found that music also had an increased role in the lives of bilateral implant participants; however, this score difference was not indicated. For the between-group comparison of unilateral, bilateral, and listeners with normal hearing, music sounded more natural to 82.6% of bilateral recipients compared to 39.1% of unilateral recipients and more pleasant to 80% of the bilateral participants as opposed to 56.5% of the unilateral participants. Significant differences between the three groups were also found for the reasons for listening to music whereby 91.3% of the bilateral group as opposed to 30.4% of the unilateral group reported 'to be happy', 78.3% of bilateral users compared to 17.4% of unilateral users reported 'to relax' and 56.5% of bilateral recipients as opposed to 13% of unilateral recipients reported 'to influence my mood.' One difference between the implant groups was that the bilateral group had more reasons for listening to music than the unilateral group. For example, the bilateral implant participants gave 2-4 reasons for listening to music, whereas 80% of the unilateral users did not give a reason at all for listening to music.

Discussion

A limitation that is consistently encountered across the examined studies is the lack of information regarding the etiological factors behind the hearing loss, how the implant was fitted, compression characteristics and microphone sensitivities, and different volume settings of the speech processor. For example, in the Schleich, Nopp, and D'Haese (2004), all subjects used the TEMPO+ speech processor with the microphone situated above the pinna. Therefore, the participants could not use spectral cues introduced by the pinna since in-pinna CI microphones are rare.

Except for one study by Schleich, Nopp, and D'Haese (2004), no mention was made on whether participants had experience with using their normal everyday program, whether this program was used in the testing process or whether the volume level on the left and right side was held constant and set to a comfortable level so that the loudness level remained the same for both sides (Schleich et al., 2004). Participants had a large range in terms of the number of months of experience with their current CI condition. Some participants received simultaneous implantation while others received sequential CIs. Therefore, the variable periods of experience along with the variable time course of acclimatization may have skewed the results. For example, participants in the Schleich, Nopp, and D'Haese (2004) study used their implant for only one month before being tested, whereas the participants in the Ricketts, Grantham, Ashmead, Haynes, and Labadie (2006) study were tested 4 to 7 months, and retested at 12 to 17 months after activation and thus had more experience and greater chance of acclimatization with their implants.

After critical evaluation of the studies presented, a significant level of evidence was present in each study. Despite the limitations, they were not great enough to question the consistent outcome. All of the studies agreed that patients with two implants can share the same binaural advantages of participants with normal hearing. However, most practicing clinicians contend that the benefits of receiving a second implant have only been proven in research and laboratory conditions with very little real-world application. Furthermore, limitations in funding in the public health care system have put constraints on major hospitals in providing a second implant to the adult population. Extensive waiting times and lack of funding can fuel the notion that a second implant is not a viable solution in the postlingually deafened population, even though research has shown significant improvement in challenging listening conditions and music perception experiences.

Clinical Implications and Recommendations for Future Research

For postlingually deafened, bilateral implant recipients who continue to exhibit difficulty in challenging listening conditions (poor lighting, speaker at a distance, and noisy situations), auditory rehabilitation programs may prove to be useful. In the past, the Listening and Communication Enhancement (LACE) program has been used with hearing aid recipients to improve their listening skills in noisy situations. A similar program, such as the Computer Assisted Speech Training (CAST) can be considered for use with adult implant recipients since the training modules can be completed at the individual's own convenience. As adult eligibility for bilateral implants continue to rise, aural rehabilitation groups should be considered and may include sessions on integrating sounds from the second implant, listening without visual cues, and strategies on communicating in group situations. Future research may consider incorporating more real-world testing conditions and extending the retest period to re-evaluate bilateral implant patients 2 to 4 years after receiving their second implant to greater examine the influence of experience and training. Since many studies tend to use a fixed-SNR task, future research should continue to use more challenging testing conditions through the use of an adaptive-SNR procedure. There continues to be limited subjective research on music perception in adults with bilateral implants due to the difficulty in recruiting a sufficient number of participants. Until we have a greater number of bilateral recipients in the adult population, it will continue to be challenging in investigating music perception, especially through subjective reports. Since most of the research in bilateral implantation is objective in nature, subjective, situational-based responses in the adult population may be more clinically relevant. Since the rehabilitation for cochlear implants includes numerous follow-up appointments, patients can comment on their own progress in different listening situations and submit their responses to the audiologist at later appointments.

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