Critical Review:
Is extended bandwidth in hearing instruments associated with improved auditory skills, compared with limited bandwidth, for the pediatric population?

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This critical review examined the effect of extended bandwidth in hearing instruments on improvement of auditory skills in children with hearing loss. Study designs included: four repeated measures within-subject design and one mixed design. Overall, the evidence supported the beneficial effects of extended bandwidth in hearing instruments on auditory skills in children with hearing loss. Children showed improvement in word learning and word recognition when the signal was presented in the extended bandwidth condition. These results should be taken into consideration for the development of future hearing instruments.

Introduction

Providing high frequency information to adult hearing impaired listeners often does not improve speech recognition scores (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Adults who acquired hearing loss later in life have already developed language skills. They have become accustomed to listening to limited bandwidth signals (Boothroyd & Medwetsky, 1992). However, children are still in the process of learning speech and language. Many sounds of speech occur in the high frequency range, such as fricatives and affricates (Elfenbein, Hardin-Jones, & Davis, 1994). The signal degradation caused by the restrictive bandwidth may be detrimental to language development.

An important fricative that children learn is /s/, which can be used to denote plurality and possessiveness (Rudmin, 1983; Nissen & Fox, 2005). The spoken /s/ has peak energy in the 6.3 – 8.8 kHz range for female and children speakers (Nittrouer, 1995). Typical hearing instruments may limit the audibility of /s/. This is especially important for children, since their caregivers are often females. The limited audibility may cause inconsistent exposures to /s/, resulting in possible phonological delays. It is very important for children with hearing loss to receive the full auditory signal, in order to have the best chance at developing normal auditory skills.

One way to provide children with more high frequency information would be to extend the bandwidth available in commercial hearing instruments. As of present, available hearing aids offer a bandwidth of about 5-6 kHz. Expanding the signal range would hopefully increase the amount of auditory information available to children.

Objectives

The primary objective of this review is to critically evaluate the existing literature on the benefits of extending the bandwidth available in hearing instruments to improve auditory skills in children with hearing loss. A secondary objective is to propose an evidence-based recommendation regarding the implementation of extended bandwidth in future hearing instruments for children.

Methods

Search Strategy

Computerized databases, including PubMed, CINAHL, Proquest, Web of Science, and Scopus were searched using the following search strategy: (extended bandwidth) AND [(amplification) OR (hearing aid) or (hearing instrument)] AND (child*). The search was limited to peer reviewed articles written in English between 2000 and 2009.

Selection Criteria

Studies included in this critical review were required to investigate the effects of extending the bandwidth in hearing instruments on the detection, recognition, or word learning abilities of children with hearing loss. A limit on the demographics of the research participants was restricted to individuals 18 years of age or younger. No limits were set on other demographics (gender, culture, race, or socioeconomic status) of the research participants. No limits were set on measures used or types of speech stimuli used.

Data Collection

Results of the literature search yielded five articles consistent with the selection criteria: four within-group studies with repeated measures and one mixed study.

Results

Within-group Studies

Kortekaas and Stelmachowicz (2000) wanted to examine the detection and clarity of word final /s/ morpheme for children and adults with normal hearing. To measure detection ability of /s/, psychometric functions were taken as bandwidth varied. Bandwidth varied between 0.25 and 9.25 kHz, with a starting bandwidth of 6.25 kHz. Participants were asked to indicate which word in a set of three was in plural form. The answer increased or decreased the bandwidth until the step size of 375 Hz was reached. Clarity ratings were measured on a scale of 1 (not clear) to 5 (very clear). Each word was presented three times at each bandwidth, ranging from 0.25 to 7.75 kHz.

Non-parametric tests indicate that a significant difference in the bandwidth detection threshold is present between all age groups. Clarity ratings only produced a significant difference for correlation between younger children and adults. A few considerations need to be made about the results. Words were presented by a male speaker, whose speech falls within a lower bandwidth. Only two words (drink and truck) were used, which can limit the generalizability to other words and phonemes. All the participants have normal hearing, making it difficult to extrapolate the results to hearing impaired people. The results do not provide sufficient evidence to infer that extended bandwidth improves detection or clarity due to the type of participants and the presence of nuisance variables.

Stelmachowicz, Nishi, Choi, Lewis, Hoover, Dierking, and Lotto (2008) measured children's ability to repeat words heard in either a 5 kHz bandwidth condition or 10 kHz bandwidth condition. There were 24 children with normal hearing aged 6-7 participating. Fourteen two-syllable nonsense words were created, spoken by a male and female talker. The children had to repeat each word twice. Two people judged the responses and transcribed each response.

A repeated measures ANOVA was performed with bandwidth and talker as within subject variables. There was a significant performance effect for the male talker ($p < .01$) and for bandwidth ($p < .001$). The researchers also wanted to learn if there was a bandwidth effect present for each phoneme used in the nonsense words. T tests were performed and a significant effect was only present for /th/ and /f/. One noticeable result was the lack of bandwidth effect for the phoneme /s/ spoken by the female talker. It was hypothesized that this may be due to differences in procedures from previous studies and children's prior phonological knowledge. The within-subject design represents a fairly high level of evidence. This study performed procedures that best matched the questions the researchers were trying to answer. One consideration for future research would be to include children with hearing loss. All the children included had normal hearing, which makes it difficult to extrapolate to hearing impaired children. Based on this, the ability of children to repeat words does show improvement when listening in an extended bandwidth condition.

Pittman, Lewis, Hoover, and Stelmachowicz (2005) examined rapid word learning in sixty children with normal hearing and thirty-seven children with mild to moderately severe hearing loss, aged 5-14 years. Effect of stimulus bandwidth was also measured. Eight nonsense words were created and embedded within a story read by a female talker. Children heard the words with a randomly chosen low pass filter of 4 kHz or 9 kHz. Word learning was assessed immediately after hearing the story through an identification task. Each word was presented 10 times in random order.

A one-way analysis of variance (ANOVA) indicated a significant difference in word learning between children with normal hearing and children with hearing loss. With the different bandwidths introduced, both groups showed small increases as the bandwidth increased (3.4% increase for normal hearing children and 5.3% increase for hearing impaired children). However, a univariate ANOVA indicated no significant effect of bandwidth. One potential problem with this study is the choice of phonemes used. Twenty four different phonemes were chosen to create the words, but no consideration was taken to ensure the words reflect the frequency of phonemes occurring in English. Future studies should include more phonemes from the fricative class, which occur more frequently. This study shows that children with normal hearing differ from children with hearing loss, in terms of word learning abilities. Due to the lack of a significant bandwidth effect, more information would be needed before implementing higher bandwidth hearing aids into clinical practice.

Pittman (2008) measured dynamic word learning rate across different bandwidths in a group of normal hearing and sensorineural hearing impaired children. Thirty-six normal hearing children and 14 moderate to severe hearing impaired children aged 8-10 years

participated. Five nonsense words were created and paired with pictures of nonsense toys. Both groups of children were divided into two groups, where they heard the signal presented in 4 kHz bandwidth or 9 kHz bandwidth. The lack of counterbalancing was due to the task the children had to perform. Words were recorded and presented by a female talker. The number of exposures to acquire the new words for each child was measured.

Exponential growth curves were created for each child to show the number of required exposures to learn the words. When comparing hearing status, children with normal hearing performed better than hearing impaired children. Children in the extended bandwidth condition, regardless of hearing status, performed better than the limited bandwidth condition. A univariate analysis of variance showed that a bandwidth effect was present, but no effect for hearing status. In other words, children required fewer exposures to learn the new words when in the extended bandwidth condition, regardless of hearing status. Children learned words much more quickly when provided with a speech signal that encompasses a wider bandwidth. This study format indicates a fairly high level of evidence. One potential problem with the procedure is the lack of counterbalancing in the bandwidth groups. Each group either received the signal in a limited bandwidth or extended bandwidth, but not both. The results do indicate that extended bandwidth does provide benefit to children with hearing loss. Consideration of these results should occur when developing hearing aids in the future.

Mixed Study

Stelmachowicz, Lewis, Choi, and Hoover (2007) examined the effects of bandwidth on a range of auditory skills. Children with normal hearing and hearing loss participated in tasks of nonsense syllable perception, word recognition, novel word learning, and listening effort. Thirty-two children with normal hearing and 24 children with mild to moderately severe hearing loss, ranging in age from 7 to 14 years, participated in this study. The children were grouped according to hearing status. The nonsense syllable perception tasks had children choose which phoneme was heard when presented in a VC context. Word recognition was performed to have a baseline measure. Twenty-five filtered and twenty-five unfiltered PBK words were presented to the children and had them repeat the words back. The novel word learning task presented a story to the children with eight CVC nonsense words embedded within it. Half of the words were filtered at 5 kHz and the other half was filtered at 10 kHz. After the story, the children had to choose the picture that matched the nonsense word that was heard. Listening effort was assessed by having the children perform two tasks concurrently. The two tasks were a word recognition task, with words filtered at either 5 kHz or 10 kHz, and a digit recall task. The percent correct score for each task was recorded.

Three-way mixed analysis of variance (ANOVA) was calculated for each task. Hearing status and age were the between-subjects variable and bandwidth was a within-subjects variable. The nonsense syllable task showed a significant bandwidth effect for the normal hearing children, but not for the hearing impaired children. The lack of bandwidth effect for the hearing impaired children seems to result from increased errors for two specific phonemes: /f/ and /v/. The bandwidth effect was greater for the hearing impaired children for the phonemes /s/ and /z/. Results for the word recognition task indicated a significant effect for bandwidth ($p < .001$). Novel word learning did not produce a significant bandwidth effect. Listening effort produced better performance on the single-task condition than the dual-task conditions. There does not appear to be an improvement in performance in the wider bandwidth for either group. The ANOVA results show no significant effects of bandwidth condition. Overall, a bandwidth effect exists for tasks that are simpler and do not involve memory. Novel-word learning and listening effort did not show an effect of bandwidth. Both of these tasks are more complex than the other tasks and require memory. Due to the high level of evidence, it does appear that children perform better on nonsense syllable tasks and word recognition tasks when listening to an extended bandwidth signal.

Discussion

Based on the articles discussed above, children experience benefit from listening to a signal that encompasses a wider bandwidth. Children with both normal hearing and hearing loss perform better when listening in an extended bandwidth condition. However, some studies do present some variable findings. The studies conducted by Stelmachowicz, Lewis, Choi, and Hoover (2007) and Pittman, Lewis, Hoover, and Stelmachowicz (2005) did not produce a significant bandwidth effect for children with hearing loss. The lack of similar results may be due to differences in the procedure for the studies. The studies also used varying age ranges. Some studies (Kortekaas and Stelmachowicz (2000); Stelmachowicz, Lewis, Choi, and Hoover (2007); Pittman, Lewis, Hoover, and Stelmachowicz (2005)) used large age ranges, while the other studies (Pittman (2008); Stelmachowicz, Nishi, Choi, Lewis, Hoover, Dierking, and Lotto (2008)) had more restricted age ranges. The age of the child may

have also played a role in how much benefit was received from the extended bandwidth. Finally, not all studies investigated the bandwidth effect on hearing impaired children. The studies by Kortekaas and Stelmachowicz (2000); and Stelmachowicz, Nishi, Choi, Lewis, Hoover, Dierking, and Lotto (2008) only included children with normal hearing. It is difficult to extrapolate the results to children with sensorineural hearing loss. Even though all studies did not find a significant bandwidth effect, all studies demonstrated that children's word learning performance improved when listening in the extended bandwidth condition. Overall, when children with hearing loss are provided with an extended bandwidth signal, they are able to extract more information then when the bandwidth is restricted.

Conclusion

Unlike adults, children appear to benefit when presented signals with larger bandwidth. Children are able to use information in the extended band to recognize words and learn new words. Children are still in the process of learning speech and language. They can benefit from more high frequency information, allowing them to access all the sounds of speech. Children with hearing loss can especially benefit from a more encompassing signal, providing them access to speech sounds they may not have heard before. Hearing impaired children need this broader signal to learn speech sounds to be on par with their hearing peers. There are a couple of considerations about applying these results to real hearing aids. All of the studies discussed above only included children with a maximum hearing loss up to the severe range. Currently, no studies have been conducted to determine whether children with severe hearing loss or worse would benefit from the broader bandwidth. Another consideration is that every child with hearing loss is different from other hearing impaired children. As these previous studies indicate, most children appear to benefit from the broader signal. However, not every child may experience that benefit. It would be important to consider all of these points before developing hearing aids that provided an increased bandwidth signal.

Clinical Implications

Currently, hearing aids on the market do not provide much high frequency information. Most commercial hearing aids provide a bandwidth range of 5-6 kHz. However, based on the results shown above, engineers should consider developing hearing aids that can process a wider signal. This processing strategy should be included in hearing instruments that are marketed more toward children. Children appear to benefit from the extended bandwidth signal, whereas adults do not gain much benefit. When implementing a wider bandwidth into hearing aids, high frequency speech sounds should be audible. As mentioned earlier, the peak energy for the phoneme /s/ occurs between 6.3 – 8.8 kHz when spoken by a female or a child. The bandwidth in hearing aids should be able to pick up that high frequency energy. It would appear that the bandwidth should extend to at least 9 kHz, in order to provide useful information. There are a couple of difficulties that may need to be overcome before implementing the extended bandwidth in hearing instruments. First, due to the presence of standing waves, it is difficult to determine accurate real ear measurements above 4 kHz (Pittman, 2008). Second, excessive loudness may occur when high frequencies are amplified. However, the children in the studies discussed above seem to appreciate hearing when in the higher frequency condition. When hearing aids are developed with this expansive signal, most children with sensorineural hearing loss should be encouraged to wear these hearing instruments, at least on a trial basis. Most children should find benefit in the use of these hearing instruments, especially in regards to word recognition and word learning tasks. However, as mentioned above, hearing impaired children are a very heterogeneous group. There may be some children who do not find benefit or who may even worsen with the broader signal. The children should be assessed and monitored frequently to ensure they are experiencing an advantage from the hearing aids with extended bandwidth.

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