

Bone Conduction Amplification in Children: Stimulation via a Percutaneous Abutment versus a Transcutaneous Softband

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Objectives: Research suggests that the speech perception of children using bone conduction amplification improves if the device is coupled to an implanted abutment rather than to a softband. The purpose of the present study was to determine if the benefit of direct stimulation via an abutment is limited to small improvements in speech perception or if similar or greater benefits occur for other auditory tasks important for learning and communication.

Design: Fourteen children (7 to 15 years of age) with bilateral conductive and three children with unilateral conductive or sensorineural hearing loss were enrolled. Each child completed four tasks while using a bone conduction device coupled to an implanted abutment and with the device coupled to a softband. The two devices were worn at the same time and activated one at a time for testing. The children completed four tasks under each coupling condition: (a) a traditional word recognition task, (b) an auditory lexical decision task in which the children repeated aloud, and indicated the category of, real and nonsense words, (c) a nonsense-word detection task which required the children to identify nonsense words within short sentences, and (d) a rapid word learning task in which the children learned to associate nonsense words with novel images.

Results: Regression analyses revealed that age, duration of device use, in-situ hearing thresholds, or device output did not account for a significant portion of the variability in performance for any of the four tasks. Repeated-measures analysis of variance revealed significant increases in word recognition with the abutment as well as significantly better performance for the lexical decision and word learning tasks. The data indicated that the children with the poorest performance with the softband tended to benefit most with the abutment. Also, the younger children showed improved performance for more tasks with the abutment than the older children. No difference between coupling conditions was observed for nonsense-word detection.

Conclusions: The improved recognition of familiar words, categorization and repetition of nonsense words, and speed of word learning with the abutment suggests that direct stimulation provides a higher-quality signal than indirect stimulation through a softband. Because these processes are important for vocabulary acquisition and language development, children may experience long-term benefits of direct stimulation for academic, social, and vocational purposes in addition to immediate improvement in communication.

Key words: Bone conduction amplification, Children, Conductive hearing loss.

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INTRODUCTION

Hearing losses can range widely in type, degree, configuration, and symmetry. People who are hard of hearing with losses

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at the extremes of these categories typically require specialized hearing devices. One such extreme is permanent conductive hearing loss, which is often best remediated with bone conduction amplification. Indeed, the variety of bone conduction devices available to children and adults has expanded significantly in recent years (Snik et al. 2005; Reinfeldt et al. 2015). Figure 1 shows the four general categories of bone conduction devices that are currently available to patients. The devices are arranged by the location of the transducer (percutaneous and transcutaneous) and by the type of coupling to the temporal bone (direct and indirect). Briefly, transcutaneous devices provide indirect stimulation of the temporal bone via coupling to a softband, flexible wire frame, or implanted magnet. Because the processors of these devices are located externally, the amplified signal must pass through layers of skin, fat, hair, and/or a magnet. These devices are most effective if they adhere tightly to the skull, which can cause some skin irritation and discomfort for the user. Percutaneous devices, on the other hand, directly stimulate the temporal bone via an implanted transducer or abutment. Although intermediate layers do not attenuate the amplified signal, other problems can occur. The abutment site can become infected without daily care, the skin can become irritated or grow over the abutment, the screw onto which the abutment is attached may fail to osseointegrate, or the abutment can be damaged by trauma (Reinfeldt et al. 2015). Children tend to experience more adverse tissue reactions than adults (Holt et al. 2008), but the overall rate of this type of complication is relatively low (8 and 4%, respectively). Likewise, children are more likely than adults (2 and 0.3%, respectively) to experience implant loss due to lack of osseointegration or to trauma (Johansson 2018).

These and other issues have prompted investigators to determine the coupling method that best optimizes hearing and health for device users. The lower portion of Figure 1 shows several recent studies comparing performance within and across different device categories. Because percutaneous devices (far left) have been shown to provide the best in-situ hearing thresholds and

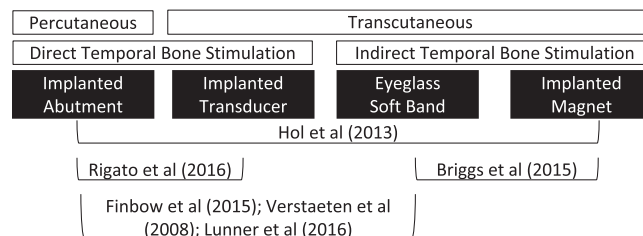


Fig. 1. Schematic showing the four general categories of bone conduction devices except dental devices. The devices are arranged by location of the transducer (transcutaneous and percutaneous) and by type of coupling to the temporal bone (indirect and direct). The lower portion of the figure shows several recent references to studies comparing the different device categories.

sound quality (Reinfeldt et al. 2015), many studies include this configuration as a reference condition. For example, Rigato et al. (2016) compared performance for conventional audiometric measures (e.g., thresholds for warble tones, speech recognition in noise) in six adults with an implanted abutment and six adults of similar age and gender with an implanted transducer. In this study, both processors transmitted the amplified signal directly. Their results were similar to preceding studies that showed better hearing thresholds in the highest frequencies (6 and 8 kHz) for the participants with an implanted abutment compared to the participants with the implanted transducer. Also similar to previous studies was the lack of differences between the groups for the speech recognition task.

Briggs et al. (2015) examined the speech perception of patients using a device on a softband to performance with the same device on an implanted magnet. In this study, both processors transmitted the amplified signal indirectly. The participants were 17 adults with bilateral conductive losses and 10 adults with single-sided deafness. The results revealed no difference in speech perception in quiet or in noise between the two indirect coupling conditions indicating that the primary, and perhaps only, benefit of the implanted magnet was the discontinuation of softband use.

Busch et al. (2015) examined speech perception and speech reception thresholds prospectively in 11 adults with implanted abutments for percutaneous devices from two different manufacturers. Although the aided thresholds at 4 and 6 kHz were better for one device, patients preferred the other device in terms of sound quality, handling/operation, and feedback/wind noise. These results suggest that traditional audiometric tests may not reveal some of the benefits experienced with bone conduction hearing devices.

In a similar study, Kara et al. (2016) examined audiometric thresholds and speech discrimination scores for a group of 16 adults and 1 child with an implanted abutment and for a group of 5 adults and 2 children with an implanted magnet. Each group was also tested with a softband. The results showed significantly better hearing thresholds with the abutment compared to the magnet or the softband, particularly in the high-frequency region. Although speech perception scores were not provided, significantly better performance was reported for the abutment compared to the softband at a conversational level (65 dB SPL), whereas no difference in performance was observed between the magnet and the softband conditions at this level.

In an earlier and more comprehensive study, Verstraeten et al. (2009) examined the performance of 10 adults with bilateral conductive losses using their own bone conduction devices. The device was coupled to an abutment, a softband, and to a testband used during clinical evaluation. As expected, significantly better hearing thresholds (10 to 20 dB) were achieved with the abutment than with the softband or the testband. To evaluate speech perception, stimuli were presented at three or more input levels allowing a comparison of performance-intensity functions across coupling configurations. These functions revealed that while speech perception differed by 10% at high conversational levels (i.e., 70 dB SPL), the difference increased to 80% at lower conversational levels (i.e., 55 dB SPL) with the poorest performance occurring under the softband condition. These results suggest a precipitous loss of amplification with softband coupling as input level decreased.

Children

The literature regarding bone conduction amplification in children with bilateral conductive losses or single-sided deafness is limited but similar to that of adults. These devices have been successfully used with a softband for a wide range of ages (6 months to 18 years) (Christensen et al. 2010b; Nicholson et al. 2011). Implanted abutments used by older children provide significantly more gain (Hol et al. 2005), better speech perception in noise, and other subjective benefits (Christensen et al. 2010a; Hol et al. 2013) compared to the softband. Also, parents and caregivers of younger children with an implanted abutment (<5 years of age) have reported improved quality of life compared to life with a softband (Amonoo-Kuofi et al. 2015).

A small but comprehensive study by Hol et al. (2013) examined the performance of children with an implanted magnet compared to that of children with an abutment. Although the participants did not serve as their own controls in this study, the groups were well matched for age, gender, and etiology of hearing loss. As with adults, the results showed that aided air conduction thresholds were better with the abutment at 2 and 4 kHz compared to the magnet. Skull simulator measures confirmed that the output of the devices was ~10 dB higher with the abutment than with the magnet. The children's audiometric results concurred with the threshold data showing better speech reception thresholds (-7 dB) and word recognition (+7%) with the abutment than with the magnet.

Despite the benefits to speech perception, there is substantial concern regarding the implanted abutment among parents and caregivers due to the higher rate of complications in the pediatric population (one in four children) compared to adults (Dun et al. 2012). For most parents, the small improvements in hearing threshold and word recognition is not enough to justify the risk of surgery and the required commitment to care and upkeep of the abutment.

Purpose

The purpose of the present study was to determine if the benefit that children receive from the implanted abutment over the softband is limited to small improvements in speech perception or if similar or greater benefits occur for other auditory tasks important to learning and communication. In the present study, children completed four tasks with a bone conduction device coupled to an abutment and with the same device coupled to a softband. The four measures were as follows:

1. A traditional word recognition task using standard audiometric speech materials;
2. An auditory lexical decision task in which the children repeated aloud, and indicated the category of, real and nonsense words;
3. A rapid word learning task in which the children learned to associate nonsense words with novel images; and
4. A nonsense-word detection task that required the children to identify nonsense words within short sentences.

In these tasks, nonsense words served as proxies for new words that are unknown to a child. Thus, these tasks represent the processes involved in recognizing unfamiliar words and learning them both in isolation and in context as well as learning new words. It was hypothesized that if direct stimulation of

the temporal bone is superior to indirect stimulation, then the performance for these tasks will be better when using a device coupled to an abutment than to a softband.

MATERIALS AND METHODS

Participants

A total of 17 children with hearing loss (10 boys, 7 girls) participated in this study. They ranged in age from 7 years, 4 months to 15 years, 1 month (mean: 11 years, 1 month). Fourteen children had bilateral conductive losses, two children had unilateral conductive losses, and one child had single-sided deafness. All three children with unilateral losses had normal or near-normal hearing in the better ear. All of the children were current users of at least one implanted bone conduction device (Ponto, Oticon Medical). Figure 2 shows the average bone conduction and binaural unaided air conduction hearing thresholds (± 1 SD) as a function of frequency. Unaided air conduction thresholds were obtained in the sound field. The better ear of the three children with unilateral losses was not occluded or masked during audiometric or experimental testing.

Each child was fitted with two new bone conduction devices (Ponto Plus Power, Oticon Medical). At the time of this study, this commercially available device provided the highest maximum force output with which to optimize the fitting. To blind the children to the activated device, both devices were worn on the same side of the head at the same time. The devices were coupled to the child's implanted abutment and to a softband as shown in Figure 3. Devices were placed on the right temporal bone for 6 children and on the left temporal bone for 12 children. Bone conduction (BC) in-situ thresholds were measured with each device which were optimally fitted for each of the two coupling conditions. The output of each device was confirmed via skull simulator (SKS-10, Interacoustics). The upper panel of Figure 4 shows the average (± 1 SD) output of each device as a function of frequency. The lower panel shows the difference in device output when coupled to the abutment compared to the softband. Note that device output was 4 to 10 dB μ N lower between 1 and 8 kHz with the abutment than with the softband, with the largest difference at the highest frequency. This is consistent with Verstraeten et al. (2009) who reported 6 to 10 dB higher output for the softband than with the abutment at frequencies ≥ 1 kHz.

The upper panel of Figure 5 shows the average (± 1 SD) BC in-situ hearing thresholds as a function of frequency for each

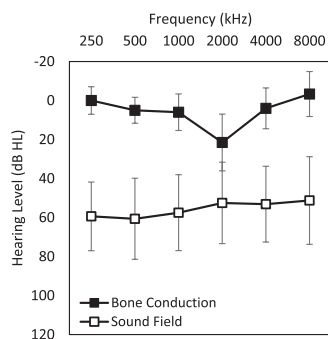


Fig. 2. Average (± 1 SD) bone conduction (filled symbols) and binaural sound field (open symbols) hearing thresholds as a function of audiometric frequency.

device. The lower panel shows the improved in-situ hearing thresholds for the abutment compared with the softband. A comparison of Figures 4 and 5 reveals that, despite the higher output with the softband, lower (better) hearing thresholds were obtained with the abutment. The improved thresholds ranged from 6 to 20 dB between 0.5 and 8 kHz, with the largest difference at the highest frequency. This is also consistent with previous studies in adults (Kara et al. 2016; Lunner et al. 2016) and indicates that direct stimulation of the temporal bone provides more effective signal transmission.

Experimental Tasks

Each child completed one task with each device configuration before proceeding to the next task. The order of the tasks and the coupling conditions (softband and direct) were counterbalanced across children. For the word recognition task, the children repeated 25 words from one NU-6 word list under each coupling condition. Their verbal responses were captured with a digital recorder and scored at a later time by one of the examiners. This was necessary to prevent any bias during real-time scoring (e.g., unknowingly repeating the utterance to be consistent with the stimulus) and to provide multiple attempts at scoring for children who did not or could not speak clearly.

For the auditory lexical decision task (Pittman & Rash 2016), the children were asked to listen to a word (one to three syllables in length), repeat the word aloud, and then indicate on a touchscreen monitor if the word they heard was real or not real. Their verbal responses were also recorded and scored at a later time by an examiner. Each list of 24 items contained equal numbers of real and nonsense words presented randomly. The experimental software provided visual reinforcement for correct categorizations of each word but not for incorrect responses. Overall performance was calculated only for words correctly categorized and correctly repeated.

In the rapid word learning task, the children were instructed to associate three nonsense words with three novel images using an interactive computer game (Pittman 2008, 2011). Each nonsense word was presented in singular and plural forms by including the phoneme /s/ at the end of the plural form. Singular and plural forms of the novel images were displayed on separate response buttons on a touchscreen monitor for a total of six response buttons. During the task, the children selected an image



Fig. 3. Bone conduction devices fitted to a softband (upper left) and to the child's abutment (lower right). The devices were worn simultaneously during testing but activated one at a time.

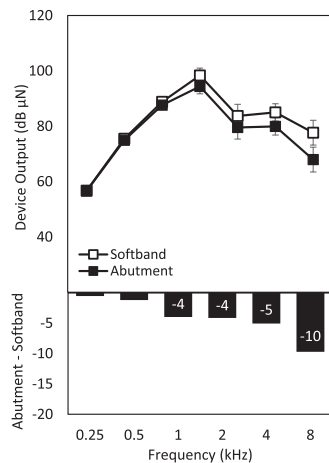


Fig. 4. Upper panel: average (± 1 SD) skull-simulator output levels for the bone conduction devices coupled to the softband (open symbols) and to the abutment (filled symbols). Lower panel: average difference in device output as a function of frequency for the implanted abutment compared to the softband condition.

after hearing each nonsense word. If they selected correctly, a video game (e.g., dot-to-dot, puzzle) advanced one step, whereas nothing happened if they selected incorrectly. Using this trial-by-trial feedback, the children learned to associate the correct word with the correct image. The six words (three singular and three plural) were repeated 15 times each for a total of 90 randomized trials that required approximately 5 min to complete. Performance across the 90 trials was analyzed in blocks of 10 trials each. This yielded nine chronological data points. A line fitted to the data points revealed the number of trials needed to reach 71% correct performance which was considered the threshold of learning [see Pittman (2008, 2011) for a detailed description of this calculation].

For the nonword detection task, children identified nonsense words embedded into four-word sentences. Two lists of 19 sentences were compiled. Each list had five sentences with no nonsense words, eight sentences with one nonsense word (two sentences with nonsense words in each of the four word positions), and six sentences with two nonsense words (two sentences with zero, one, or two words between the two nonsense words). The 20 nonsense words in these sentences were created by replacing a single phoneme within a word(s). The replacement phonemes were selected to maintain the phonotactic probability of the original word (Vitevitch & Luce, 2004). For example, the phoneme /d/ in the word “food” was replaced with an /m/ to create the sentence “Cooks make hot *foom*.” Likewise, the sentence “*Foy traibs* move fast” originated from “Toy trains move fast.” The children were instructed to listen to each sentence and identify the position of each nonsense word or words within the sentence. To do this, they selected the appropriate word position displayed as numbered buttons (1, 2, 3, or 4) on a computer monitor. Buttons could be unselected if necessary. When satisfied, they proceeded to the next stimulus by selecting a button labeled “Next” after which reinforcement for correct responses was provided in the form of a video game.

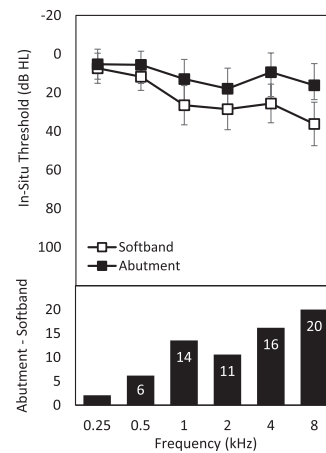


Fig. 5. Upper panel: average (± 1 SD) BC in-situ hearing threshold levels for the bone conduction devices coupled to the implanted abutment (filled symbols) and to the softband (open symbols). Lower panel: average improvement in threshold as a function of frequency for the abutment compared to the softband condition.

Procedure

The stimuli for all of the tasks were produced by the same female talker with a standard American English dialect. They were recorded at a sampling rate of 44.1 kHz, 16-bit resolution using a microphone (AKG, C535 EB) with a flat frequency response from 0.1 to 10 kHz (± 2 dB). All testing was conducted in a sound-treated room. The children were seated 1 m from a loudspeaker placed at 0° azimuth. Custom laboratory software was used to randomly select the stimuli, equalize the RMS level, present the stimuli at 50 dB SPL (re: calibrated position), and provide reinforcement.

The Institutional Review Board at Arizona State University approved this study. Before testing, informed assent was obtained from the children, with written consent from the parents. Each test session lasted between 1 and 2 hr. Children were paid \$25 per hour for their participation.

RESULTS

Regression Analyses

Before comparing performance across coupling conditions, the data were subjected to regression analysis to determine if any demographic factors accounted for a significant portion of variability in performance. A separate regression analysis was conducted for each task with the difference in scores between the abutment and the softband condition entered as the dependent variable. Age, years amplification, aided threshold difference (dB HL), device output difference (dB μ N) and normalized aided threshold and output differences were entered into the regression model in a stepwise fashion. Normalized values were calculated by taking the difference between the softband and abutment values relative to the abutment value. The resulting proportions represented the relative benefit or detriment from abutment use independent of the absolute degree of hearing loss or device output.

The results show that none of the variables entered accounted for the difference in softband and abutment performance for the word recognition ($F(7,13) = 1.901$, $p = 0.226$), lexical decision ($F(7,13) = 1.468$, $p = 0.328$), nonsense-word

detection ($F(7,13) = 1.668, p = 0.258$), and the word learning ($F(7,13) = 0.872, p = 0.575$) tasks. On the one hand, these results indicate that the children represented a homogenous group in terms of age and hearing history. On the other hand, the results indicate that differences in aided hearing thresholds and output levels did not vary systematically with performance on any task. Thus, significant differences in performance between the two conditions on the behavioral tasks would suggest that measures of auditory threshold and device output are not sensitive indices of benefit or detriment.

Word Recognition

Figure 6 shows word recognition scores for the abutment condition as a function of the softband conduction. Each of the 16 data points represents an individual child. Data for one 12-year-old child was unavailable due to failure to start the digital recorder during testing. The diagonal dashed line represents equal performance for each condition. The filled symbols represent the children with bilateral conductive losses and the open symbols represent the children with unilateral losses. Average performance (± 1 SD) for each condition is also shown (square symbol).

With the exception of one child whose word recognition improved from 0 to 40% with the abutment, little difference in performance was observed across devices. As in the study by Hol et al. (2013), word recognition improved 7%, on average, with direct stimulation via the abutment compared to indirect stimulation via the softband. Before statistical analyses, the percent-correct values were arcsine transformed to equalize the variance over the large range of scores (Studebaker 1985). The data were then subjected to a repeated-measures analysis of variance (ANOVA) with coupling condition (abutment and softband) as the within-subjects factor. The results revealed significantly higher word recognition for the abutment compared to the softband, $F(1,15) = 10.3, p = 0.006, \eta_p^2 = 0.41$.

Lexical Decision Task

Like the word recognition task, the children's repetition of the real and nonsense words in the lexical decision task were scored off-line by an examiner. A recording for one 15-year-old child was unavailable, again, due to failure to start the digital

recorder. Each child's verbal responses were compared to their categorization of the words (real and nonsense) to represent the performance as the percentage of words that were correctly repeated and categorized. Thus, errors for either part of the response reduced the overall score. Figure 7 shows the performance for the individual children using the same convention as in Figure 6. For this task, larger benefits from direct stimulation via the abutment occurred for many of the children, including two children with unilateral losses. On average, the children's lexical decisions improved 13% with the abutment compared to the softband. Like word recognition, the percent-correct scores were arcsine transformed and subjected to repeated-measures ANOVA. The improvement in performance was statistically significant, $F(1,15) = 11.66, p = 0.004, \eta_p^2 = 0.44$. These results indicate that, on average, the children were better able to differentiate familiar and unfamiliar words with direct stimulation via the implanted abutment and this benefit was greatest for the children with the poorest performance with the softband.

Additional analysis of the real and nonsense words was conducted to determine whether the benefit with the abutment occurred for one type of word (real or nonsense words) or if the benefit was universal. Figure 8 shows average (± 1 SE) performance for the real and nonsense words under each coupling condition. Performance improved significantly (13%) for both types of words, real: $F(1,15) = 5.474, p = 0.034, \eta_p^2 = 0.27$, nonsense: $F(1,15) = 9.986, p = 0.006, \eta_p^2 = 0.40$, indicating a global benefit of direct stimulation rather than benefit for an easier (familiar words) or more difficult (unfamiliar words) aspect of the task.

Rapid Word Learning

For the rapid word learning task, learning was calculated as the number of trials needed to achieve 71% performance across the 90 trials. With this approach, faster learning is achieved with fewer trials to criterion performance, whereas slower learning requires more trials. Data for one 12-year-old child was excluded after he reported that he "figured out the trick" to doing the task under the second device condition, indicating that he did not understand the task under the first condition. His very poor performance under the first condition confirmed his observation. Because the first condition could not be repeated (i.e., words cannot be unlearned and

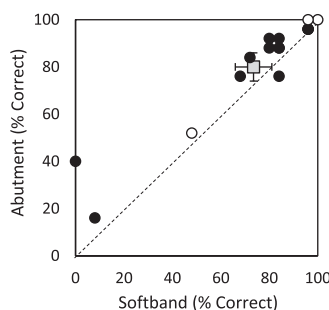


Fig. 6. Individual performance for the word recognition task for the abutment condition relative to the softband condition. Filled symbols represent the performance of children with bilateral conductive losses; open symbols represent the performance of children with unilateral conductive or single-sided deafness. The larger filled square represents average (± 1 SE) performance for each condition. The diagonal dashed line represents equal performance for both coupling conditions.

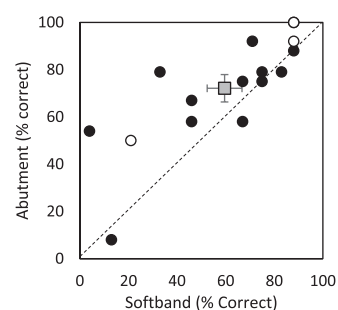


Fig. 7. Individual performance for the lexical decision task for the abutment condition relative to the softband condition. Filled symbols represent the performance of children with bilateral conductive losses; open symbols represent the performance of children with unilateral conductive or single-sided deafness. The larger filled square represents average (± 1 SE) performance under each condition. The diagonal dashed line represents equal performance for both coupling conditions.

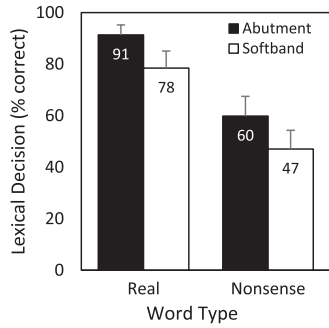


Fig. 8. Average (+1 SE) performance for the real and nonsense words in the lexical decision task for the abutment and softband conditions.

learned again), data for both conditions were excluded. Individual performance for the remaining 16 children is shown in Figure 9 using the same convention as in Figures 6 and 7. As with the lexical decision task, the children learned at the same or faster rate with direct stimulation, including the children with unilateral hearing losses. The results of a repeated-measures ANOVA indicated significantly faster learning (fewer trials to criterion) with the abutment compared to the softband, $F(1,15) = 7.63, p = 0.015, \eta^2_p = 0.34$.

To better appreciate the difference in learning rates for the abutment and softband conditions, Figure 10 shows the average (± 1 SE) performance for each of the nine trial bins arranged in the order they occurred during testing. The solid and dashed lines are the best fits to the data for each condition. These data reveal similarly shallow learning curves but consistently higher overall performance with the abutment than with the softband. Recall that learning speed was calculated as the number of trials needed to reach 71% performance, which for these conditions was extrapolated from the fitted learning curve. However, determining the number of trials required to reach 50% performance is sufficient to observe the significant differences in learning between these conditions. Specifically, to reach 50% performance the children required 24 trials with the abutment and 60 trials (more than double) with the softband. Because children cannot anticipate the number of repetitions they will receive when learning a new word, learning efficiently with the fewest repetitions is always optimal.

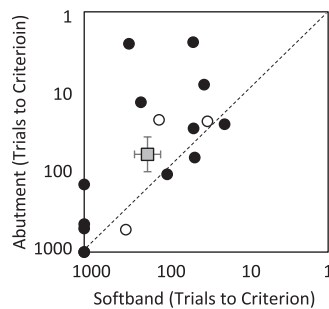


Fig. 9. Individual learning speed (trials to 71% criterion performance) for the word learning task for the abutment condition relative to the softband condition. Filled symbols represent the learning of children with bilateral conductive losses; open symbols represent the learning of children with unilateral conductive or single-sided deafness. The larger filled square represents average (± 1 SE) learning for each condition. The diagonal dashed line represents equal learning for both coupling conditions.

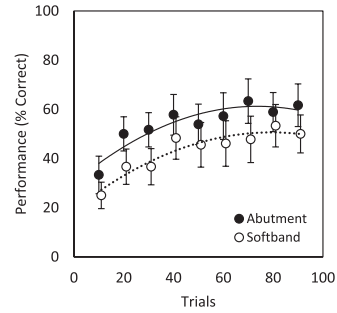


Fig. 10. Average (± 1 SE) learning as a function of trials for the abutment (filled symbols) and the softband (open symbols) conditions. Data points (jittered to display the error bars fully) represent performance for 9 bins of 10 learning trials each. The solid and dashed lines are the best fits to the averaged data points.

Nonsense-Word Detection Task

An important requirement for learning new words is the ability to detect unfamiliar words in the context of familiar ones. Opportunities to learn new words are lost if unfamiliar words are not, or cannot be, detected. Because the task required the children to detect nonsense words and ignore real words, signal detection theory was used to calculate a sensitivity index (d') from the standardized hit and false-alarm rates. In this context, a higher d' value (a dimensionless statistic) indicates that the child was better able to identify nonsense words surrounded by real words than a child with a lower d' value. Figure 11 shows the children's sensitivity to the nonsense words with the abutment as a function of their sensitivity with the softband. The results show that while many of the children benefited from direct stimulation via the abutment, many performed similarly with both devices and one child performed best with the softband. Repeated-measures ANOVA revealed no difference in sensitivity to the nonsense words between the two conditions, $F(1,16) = 2.24, p = 0.154, \eta^2_p = 0.12$, indicating that, on average, the children did not receive additional benefit from direct stimulation of the temporal bone via the abutment for this task.

Figure 12 shows the average (± 1 SE) error rate for the nonsense words that were missed (filled portion of the bars) and for the real words that were incorrectly identified as nonsense

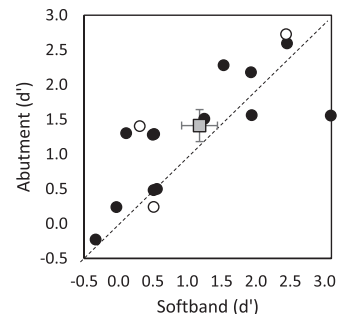


Fig. 11. Individual sensitivity to real and nonsense words in the nonword detection task. Performance is shown for the abutment condition relative to the softband condition. Filled symbols represent the sensitivity of children with bilateral conductive losses; open symbols represent the sensitivity of children with unilateral conductive or single-sided deafness. The larger filled square represents average (± 1 SE) sensitivity for each condition. The diagonal dashed line represents equal sensitivity for both coupling conditions.

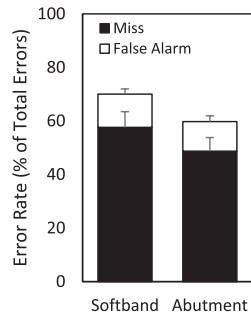


Fig. 12. Average (+1 SE) error rate for misses (filled) and false alarms (open) as a function of coupling condition.

(open portion of the bars). These error rates indicate that children with hearing loss are far more likely to ignore nonsense words than to misperceive real words as nonsense. These results are consistent with those of Pittman & Rash (2016) who showed that children with hearing loss unknowingly repair nonsense words into real words. Although not statistically significant, the error rate for missed nonsense words decreased 9% with the abutment, $F(1,16) = 2.7$, $p = 0.151$, $\eta_p^2 = 0.12$, whereas little change (1%) was observed for the misperception of real words, $F(1,16) = 0.49$, $p = 0.50$, $\eta_p^2 = 0.03$.

Across-Task Benefit

Last, it was of interest to determine if each child's benefit or detriment from direct stimulation via the abutment occurred across tasks. Difference scores between the abutment and softband conditions were calculated and the number of difference scores that indicated benefit (positive scores regardless of magnitude) were counted for each child. Figure 13 shows the number of tasks in which the children's score indicated that they benefited from the abutment compared to the softband. The data in the figure are arranged as a function of age. The results show that all but one child received benefit from the abutment for at least one task and that the younger children benefited more than the older children. The relationship between age and benefit was significant, $r = 0.51$, $p = 0.02$. Because the magnitude of the benefit is not considered in this analysis, the results indicate that the youngest children experienced benefit from direct stimulation for a wider range of auditory tasks than the older children who demonstrated benefit for just one or two tasks.

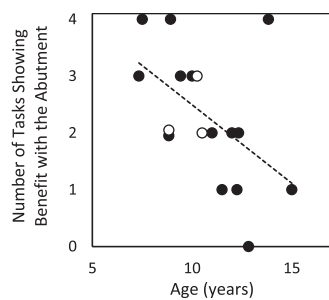


Fig. 13. Number of tasks for which performance improved with the use of the device coupled to the implanted abutment as a function of age for the children with bilateral conductive losses (filled symbols) and the children with unilateral losses (open symbols).

DISCUSSION

Recall that the purpose of the present study was to determine if the benefits that children receive from the implanted abutment versus the softband are limited to small improvements in speech perception or if similar or greater improvements occur for other auditory tasks important to learning and communication. Performance for four auditory tasks was examined to test the hypothesis that if direct stimulation of the temporal bone is superior to indirect stimulation, then the performance for these tasks would be better when using a device coupled to an abutment than to a softband. While small improvements in word recognition have been reported with an implanted abutment, it was reasoned that the risks associated with surgery and the commitment to care of the abutment site could be justified if the benefits of an implanted abutment extend to more than just the repetition of familiar words. The results replicated the benefits of direct stimulation for word recognition and showed additional benefits for differentiating familiar words from unfamiliar ones (auditory lexical decision task) and for learning new words rapidly.

These results are consistent with recent studies comparing standard audiologic measures obtained via direct and indirect stimulation of the temporal bone (Verstraeten et al. 2009; Finbow et al. 2015; Kara et al. 2016). An important contribution of this work is that the detection and learning tasks represent processes children use to learn new information on a daily basis. To learn new words, children must first determine if a word is known or unknown to them before they can attempt to assign a semantic (meaningful) representation to the word. If the child cannot identify an unknown word in isolation or within a sentence, he loses that opportunity to learn the new word or learn more about a word he already knows. These missed opportunities may be responsible, in part, for the smaller vocabularies of children with hearing loss compared to their counterparts with normal hearing (Pittman et al. 2005). Also, the results of the present study are consistent with previous studies showing that new-word detection and learning in children with sensorineural hearing loss is directly related to the quality of the acoustic signal they receive (Pittman 2008, 2011).

The results are also in agreement with work by Lunner and colleagues (2016) who reported benefits of direct stimulation for a cognitive task in which the listeners held information in memory for a short time. Specifically, 16 adults (26 to 78 years of age) were tested with the same configuration of bone conduction devices as in the present study. Each listener repeated the final word of 7 sentences (word recognition) and then repeated the seven words at the end of each list (recall). The results showed that although recognition was similarly high for the abutment and softband conditions (96%), significantly more words were recalled with the abutment (52%) than with the softband (46%). They also reported a difference in the high-frequency BC in-situ hearing thresholds with the abutment and softband similar to the differences reported in the present study. The authors concluded that working memory was enhanced by the more efficient energy transduction of the amplified signal via the abutment. Specifically, although the output of the device was higher when coupled to a softband, layers of hair and skin attenuated the signal transmission. Also, the softband coupling can cause the higher output of the device

to saturate at lower input levels and cause additional distortion of the amplified signal.

However, the results for the nonsense-word detection task (detecting nonsense words within sentences) were inconsistent with those of previous studies. For example, Pittman et al (2017) reported that the detection of nonsense words in context improves significantly with small improvements in the acoustic signal in children with sensorineural hearing loss. It is possible that stimulation from just one bone conduction device was not sufficient to overcome ambiguities in the amplified signal with either coupling condition causing children to revert to their strong repair strategies (Pittman & Rash 2016). Although bilateral bone conduction stimulation has not been shown to improve perception of familiar words compared to unilateral stimulation (Dutt et al. 2002b), bilateral implantation may provide sufficient energy transduction to optimize children's ability to identify new words in conversation and improve overall satisfaction with the devices (Dutt et al. 2002a).

Also unique to this project is that the children with unilateral and bilateral losses received similar benefit from the implanted abutment. Although the sample of children with unilateral losses was quite small ($n = 3$), they were expected to perform at the highest levels on each task because they had one normal- or near-normal-hearing ear. Instead, their performance was within the range observed for the children with bilateral losses, especially for the most difficult tasks. These results are consistent with reports stating that children with unilateral hearing losses experience significant academic, social, memory, and attention deficits (Tharpe 2008) due to functional reorganization of the brain as a result of unilateral stimulation [see Vila and Lieu (2015) for a review of the consequences of unilateral hearing loss]. Put simply, the brains of children with unilateral profound hearing loss receive auditory information from one cochlea, while the brains of children with bilateral losses (conductive or sensorineural) receive information from two cochleae. Implantation of a bone conduction device on the affected side cannot overcome the uneven stimulation to the brain but may provide a more comprehensive signal (i.e., in amplitude and bandwidth) than can be achieved with normal hearing in one ear (Christensen et al. 2010a). Direct examination of the outcomes of children with unilateral hearing losses (conductive or sensorineural) using a bone conduction device is a worthwhile area of further research.

In summary, the results indicate that direct stimulation of the temporal bone via an implanted abutment provides improved signal quality compared to indirect stimulation via a softband. In addition to small benefits for word recognition (repetition of familiar words), children can expect improved identification, repetition, and acquisition of unfamiliar words; critical processes for vocabulary and language development. The results also indicate that, with the exception of the nonword detection task, the children with the poorest performance with the softband tended to benefit the most when using the device coupled to the abutment than to the softband. Last, the younger children showed more global benefits (improved performance with the abutment for more tasks) than the older children.

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