Auditory Training for Central Auditory Processing Disorder

Jeffrey Weihing, Ph.D.,[1] Gail D. Chermak, Ph.D.,[2] and Frank E. Musiek, Ph.D.[3]

ABSTRACT

Auditory training (AT) is an important component of rehabilitation for patients with central auditory processing disorder (CAPD). The present article identifies and describes aspects of AT as they relate to applications in this population. A description of the types of auditory processes along with information on relevant AT protocols that can be used to address these specific deficits is included. Characteristics and principles of effective AT procedures also are detailed in light of research that reflects on their value. Finally, research investigating AT in populations who show CAPD or present with auditory complaints is reported. Although efficacy data in this area are still emerging, current findings support the use of AT for treatment of auditory difficulties.

KEYWORDS: Auditory training, central auditory processing disorder

Learning Outcomes: As a result of this activity, the participant will be able to (1) describe characteristics of effective AT protocols, including aspects related to the training schedule, training difficulty, maintaining motivation, and transfer of learning and (2) describe results from current research investigating AT in patients with CAPD or who present with auditory complaints.

Central auditory processing disorder (CAPD) refers to dysfunction of the central auditory nervous system (CANS) that contributes to difficulties with perceptual processing of auditory information and that is thought to contribute to delays in skills in which successful

---

[1] Division of Communicative Disorders, University of Louisville, Louisville, Kentucky; [2] Department of Speech and Hearing Sciences, Washington State University Spokane, Spokane, Washington; [3] Speech, Language and Hearing Sciences, the University of Arizona, Tucson, Arizona.

Address for correspondence: Jeffrey Weihing, Ph.D., Division of Communicative Disorders, University of Louisville, Louisville, KY 40202 (e-mail: jaweih02@louisville.edu).

Auditory Training: Consideration of Peripheral, Central-Auditory, and Cognitive Processes; Guest Editor, Jill E. Preminger, Ph.D.

Semin Hear 2015;36:199–215. Copyright © 2015 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584-4662.
DOI: http://dx.doi.org/10.1055/s-0035-1564458.
ISSN 0734-0451.

listening serves a fundamental role. CAPD affects a variety of populations and has several suspected causes, including neuromaturational delay,[1] neuroanatomical anomalies (e.g., ectopic cells),[2,3] and neurologic insult of the CANS.[4] Additionally, the term *central presbycusis* has recently been adopted to describe CAPD that results from changes to the CANS that occur as a result of aging.[5] CAPD is diagnosed using a test battery comprised of behavioral, electroacoustic, and/or electrophysiologic measures that have documented sensitivity and specificity to CANS dysfunction and that assess a range of CANS processes.[6] The primary complaints and symptoms of CAPD are auditory; however, due to the nonmodularity of brain organization, functional deficits can frequently manifest in related areas of attention, language, communication, and learning.[7]

A successful treatment plan for CAPD incorporates a variety of different approaches. These approaches include environmental modifications and assistive listening devices (e.g., frequency modulation [FM] systems), development of compensatory and metacognitive strategies, delivery of necessary services for comorbid conditions, and auditory training (AT).[6] The last of these approaches, AT, addresses the central auditory processing (CAP) deficit most directly by attempting to improve the function of the affected auditory process(es). A typical AT paradigm consists of challenging listening tasks that are not unlike those tests on which the patient showed difficulty during the CAPD evaluation. A patient completes these tasks several times a week while their performance on auditory processing tasks is monitored. Although additional benefits to related skills (e.g., attention) may be achieved through AT, the primary goal of enrolling a patient in AT is to minimize or eliminate the dysfunction in auditory processing.

The present article focuses on this important component of the CAPD treatment plan. We first consider auditory processing categories and general types of AT, as well as more specific AT programs. Next, we consider characteristics and parameters of AT intervention that can influence performance improvements seen over time. Finally, we review existing AT research that has been performed in populations diagnosed with CAPD or with specific auditory complaints that are not due to peripheral hearing loss.

AUDITORY PROCESSES AND TRAINING

Four broad types of auditory processes are measured by the tests included in the diagnostic CAPD battery. These processes include: (1) dichotic processing, in which a different speech stimulus is simultaneously presented to each ear and the patient repeats back one or both stimuli; (2) temporal processing, which is a broad category that includes skills related to processing changes to the auditory signal over time; (3) perception of monaural low-redundancy speech, in which monaurally presented speech is degraded through filtering, the addition of noise or reverberation, and/or time compression; and (4) binaural interaction (e.g., localization, lateralization), in which complimentary inputs that differ in time, intensity, or spectral characteristics of otherwise identical stimuli are combined across the ears to support the perception of an auditory signal's spatial location.[8] Some tests that have been used commonly to diagnose dysfunction in each of these areas include Dichotic Digits and the Competing Sentence test for dichotic processing, the Frequency Patterns test or Gaps-In-Noise for temporal processing, and the low-pass filtered speech test for perception of monaural low-redundancy speech.[9–14] Clinical assessment of binaural interaction is less frequently assessed by audiologists,[14] despite the availability of the masking level difference test.[15] More recently, spatial processing has been introduced as a fifth general category of auditory processing.[16] This process is assessed with the listening in spatialized noise (LiSN) test that measures spatial release from masking. In its requirement that localization cues be used for the successful recognition of speech signals, this task is similar in definition, though not completely identical, to binaural interaction tasks.

Underlying each of these processes are several more fundamental abilities, including auditory discrimination and auditory identification of differences in signal frequency, intensity, and duration.[6] From a psychoacoustic perspective, *discrimination* tasks include a same–different judgment by comparing two stimuli on the relevant acoustic dimension, and *identification* tasks include a judgment on which of three or more stimuli differs from the rest. Discrimination and identification are essential components of auditory processing, as they lay the foundation for more complex auditory processes that occur in the CANS.

A typical AT intervention, therefore, addresses one or more of these auditory processes and underlying skills. Both the results of the CAPD diagnostic battery, and the functional deficits presented by the patient (e.g., recognizing speech in noise) drive which areas are selected for training. The patient is administered training across clinical training sessions. During each session, performance attained during the prior session is examined. Upon attaining a particular performance criterion (typically 70 to 80% accuracy), the task is made more difficult to challenge the patient's auditory system and incrementally improve performance. At some set end point, auditory processing is reassessed clinically to determine patient progress on the training. At that point, it can be determined if additional training is needed, if the remediation plan needs to revised, or if the patient should be discharged from therapy.

Formal and Informal Auditory Training

Training typically is administered formally or informally.[17] The distinction between these two approaches involves the level of control that is maintained over the training stimuli and the environment, and often the nature of the stimuli used. Formal training uses recorded stimuli (e.g., tones, noise, speech, digits) presented via a computer or CD player. The stimuli may be routed through an audiometer for precise control over stimulus levels, and a sound booth may be used to minimize interference from environmental sounds. Formal training also typically utilizes some mechanism for controlled adaptive difficulty. That is to say, training difficulty is modified to maintain performance at some criterion. To determine if the criterion is met, performance is scored periodically and training difficulty is modified to bring performance closer to criterion. Some types of formal training utilize a computer-based auditory training (CBAT) approach (see later).[18]

Conversely, informal training is typically not as concerned with stimulus control. Stimuli are presented without the use of an audiometer and may be presented face-to-face instead of using recorded stimuli. As informal training is typically done at home or in school, a sound booth is not used. Stimuli are often age-appropriate words or sentences, although nonverbal stimuli can be used in informal AT as well. Informal AT tasks typically exercises multiple auditory processes concurrently and somewhat indirectly.[19]

Adaptive difficulty can be achieved with informal training, though evaluation of performance relative to the criterion is typically done less frequently and is not as precise. Whenever possible, it is preferable to do formal training over informal, or to supplement formal training with informal. If it is not possible to implement formal training, then informal training may be used in isolation.

Auditory Training Software

It is becoming more commonplace for AT to be administered using software programs and, for this reason, we consider here some of the CBAT tools that clinicians and researchers are currently using to train auditory processing. Common to these programs is the presentation of training in the context of video games to keep children engaged. Some of the programs have different versions targeted toward various age ranges so that the interface for presenting these stimuli can be made age-appropriate. When CBAT programs are targeted toward adults alone, game interfaces generally are not used.

Auditory-Language Software

Earobics was one of the earliest CBAT programs. Earobics exercises underlying auditory skills in the context of auditory-language exercises (e.g., phonological awareness). Targeted auditory skills include temporal sequencing, pattern recognition, auditory closure, auditory discrimination, and auditory performance with competing signals. The program also addresses sound–symbol correspondence as it relates to reading, phonological awareness, sound blending, following oral directions, and memory and attention. Based on a review of three studies involving children diagnosed with language learning impairment or specific reading disorder, Loo and colleagues noted improved morphology, amplitudes, and latencies of speech-evoked cortical and subcortical responses in noise following Earobics training.[20] Some positive impact was seen on phonological awareness skills; however, Earobics training had little effect on language, spelling, and reading skills of the children. Increases in the amplitude of evoked responses to speech stimuli related to brainstem and cortical substrate indicated possible improvements in electrophysiologic representation in the CANS following training with Earobics.[21,22]

Fast ForWord (FFW) is a commonly used CBAT program that, similar to Earobics, targets phonological awareness and temporal processing.[23,24] This program presents tasks within the context of language training; however, temporal processing underlies the theoretical foundation of FFW, which incorporates acoustic manipulations to adjust the difficulty of tasks. In their recent review of CBAT research, Loo et al reported that four FFW studies showed improvement in temporal tasks following training, with one showing no change in frequency discrimination and one showing improvement in speech-evoked cortical potentials (N1–P2).[20] FFW demonstrated some impact on phonological awareness skills but had little effect on the language, spelling, and reading skills of children diagnosed with language learning impairment or specific reading disorder. Possible explanations for the differences across behavioral and electrophysiologic measures are discussed later.

Dichotic interaural intensity difference (DIID) training is a formal AT procedure that can be administered using customized stimuli through an audiometer or via a CBAT program.[25] The procedure is intended for training dichotic processing interhemispheric transfer deficits and aims to improve performance in the weaker (dichotic) ear over time. This is accomplished by providing the weaker ear a listening advantage during dichotic training tasks by decreasing the intensity level in the stronger ear, as determined by dichotic test results (i.e., ear advantage). As the patient improves, the level in the stronger ear is increased to maintain the challenging nature of the task. In a variation of this procedure, interaural timing differences are manipulated instead of level differences to achieve the same effect.[26] Two CBAT programs provide dichotic training, CAPDOTS (The Listening Academy) and the soon to be released Sound Auditory Training (SAT).[27] Research with the DIID has shown that it improves dichotic listening and that gains obtained from this training are correlated with some nonauditory outcome measures, such as parent and teacher report of student listening difficulty.[28]

The LiSN and Learn is a CBAT program that was developed to treat spatial processing deficits identified using the LiSN test.[29] This CBAT approach focuses on training the ability to benefit from spatially separated speech in background competition. Research on the LiSN and Learn is considered later (see "Review of Auditory Training Research Performed on Participants with Auditory Complaints").

A new CBAT tool that is in development by the present authors is SAT. SAT is a toolkit for training a range of fundamental auditory processing skills, including auditory discrimination and identification, temporal sequencing (frequency and duration pattern recognition), gap detection, dichotic processing, binaural interaction, and auditory closure. This set of exercises allows the user to train any of the auditory processes identified by several professional consensus statements as important for listening,[6,30] and each task is interchangeable with a range of user interfaces to promote patient interest and motivation and adaptive algorithms for training efficiency.

CHARACTERISTICS OF EFFECTIVE AUDITORY TRAINING PROGRAMS

Training Schedule

Sufficient time must be devoted to AT to induce and maintain change. Intensive therapy can require considerable time, which can be distributed in regard to the length of the training session, the number of training sessions, the time intervals between sessions, and the period of time over which training is conducted.[23] It is common for clinicians to adopt a training schedule of three to four times a week for 20 to 30 minutes. Several studies have empirically examined training schedules. Molloy et al trained young adults on a frequency discrimination task for a total of 50 training blocks using several different training schedules: 800 trials a day for 2 days, 400 trials a day for 4 days, 200 trials a day for 8 days, and 100 trials a day for 8 days.[31] The shortest training sessions were ~8 minutes and the longest sessions exceeded an hour. Although all conditions yielded a similar degree of improvement following the termination of training, the shorter training sessions allowed for more latent learning, or learning that occurred between sessions. Specifically, the group that received 100 trials over 8 days improved most quickly during the early stages of training, suggesting that shorter training sessions distributed over time maximize learning efficiency. Dramatic early learning induced by AT usually is a common finding in AT research, with performance improvements generally becoming smaller over time.[32,33] This finding is also supported by neurophysiological data that shows that changes emerge within 1 to 4 days of initiating AT, sometimes even preceding improvements in behavioral performance.[34]

It should be noted that the current literature on AT does not specifically reflect on whether “booster” sessions are needed following discharge from AT to maintain auditory benefits. For instance, Anderson et al administered an 8-week program that included tasks aimed at improving: temporal order judgments of FM sweeps, discrimination of similar syllables, recognizing or matching sequences of syllables and words, implementing command sequences, and answering questions from stories.[35] Participants showed electrophysiologic, speech-in-noise, and memory benefits; however, only the electrophysiologic benefits were maintained when assessed 6 months after training. Assessment of electrophysiologic improvements from training were maintained; however, benefits seen in speech-in-noise and memory measures were not maintained when reassessed 6 months after training. The decline in memory benefits was explained by the authors as being consistent with existing research, which shows that benefits to general cognitive abilities, such as speed of processing, tend to be maintained but benefits to more specific cognitive skills, such as working memory, do not. Furthermore, the decline in speech-in-noise benefits was interpreted by the authors as reflecting the limited short-term benefit in cognition (i.e., attention and memory skills), which over time waned. Benefits measured electrophysiologically may be more persistent because they are more purely auditory and less likely to be affected by these supramodal factors. For instance, Anderson et al note that speech-in-noise ability was assessed using the QuickSIN, and this measure may place demands on attention and memory.[35] Because the QuickSIN benefits were not maintained, initial gains seen posttraining on this measure may have been related to short-term cognitive improvements that benefited attention and memory. Overall, these findings may suggest that booster sessions could be beneficial for maintaining AT gains.

Training Difficulty

AT tasks should be graduated in difficulty over time as a function of the patient’s performance.[36] Tasks should be presented systematically and employ adaptive difficulty so that the task can remain challenging and motivating, but not overwhelming. Tasks should be designed to allow patients to work at their skill threshold or edge of competency.[37] The amount or degree of progression is sometimes difficult to determine. Most software programs have sufficient flexibility to adjust incremental levels; however, the question is the size step of the progression. If the step size is too large, performance will not improve, signaling that a smaller increment in difficulty level should be introduced.[38] Appropriate increments in task difficulty have been shown in animal studies to be critical to improvement seen from training.[39]

Another variable underlying AT difficulty is the targeted success-to-failure criterion ratio. Therapy programs should be designed so that the client experiences success sufficient to maintain motivation at high levels. Success rates approaching 100%, however, usually indicate that the task is too easy and that the patient's auditory system is not sufficiently challenged to elicit optimal change. On the other end of this spectrum, several studies have shown that training effects are still witnessed even when the task is impossible for the patient to complete (e.g., when the participant is asked to discriminate two identical tones).[40,41] Although this would suggest that tasks cannot be made too difficult, one should be cautious of possibly demotivating the patient.

In contrast, some research with animals questions these findings. Edeline and colleagues measured behavioral and electrophysiologic changes in animals that received two types of AT for frequency discrimination, one considered to be easy and the other highly difficult (i.e., requiring discriminations beyond the capability of the animals).[42] Interestingly, the *easy* AT yielded definite improvements in frequency discrimination measured behaviorally, and the *difficult* AT yielded essentially no improvement. Direct measurements at the auditory cortex, however, showed improved receptive field responses for both easy and difficult tasks. As noted previously in reference to the Anderson et al study,[35] we conclude that neural timing benefits reflecting cortical auditory plasticity may be seen in the absence of certain behavioral changes, particularly when the training and/or the behavioral measures require more pervasive or more focused neural substrate that might not have been trained or reflected in the electrophysiologic measures.

Based on all findings reviewed here, we suggest that the success-to-failure ratio should be selected so that the task is challenging but not impossible to complete. To this end, a performance criterion of 70% is commonly employed,[19] and task difficulty should be adaptively modified so that performance satisfies this criterion. A balanced success-to-failure criterion ratio should be targeted (sometimes referred to as the 70–30 rule) wherein the level of difficulty is adjusted to allow the patient to achieve scores of ~70% correct and no poorer than 30%. This will help maintain motivation while providing sufficient challenge to cause change.[19]

Motivation and Performance Feedback

Keeping a patient motivated throughout training is an important factor in achieving successful outcomes from therapy, as it is for learning in general.[40,43,44] Patients who are not motivated are not likely to be successful in an AT program. To maintain motivation, the patient must understand the rationale underlying the AT. Even children need to understand that they are enrolled in AT to improve their listening abilities, which in turn may impact their social and academic success. Teachers, parents, and clinicians should explain to children, using real-world and functional examples (e.g., ability to follow a coach's directions or understand the teacher in the noisy classroom), why they are in therapy and how it will help them.

Computer-assisted AT has grown in use due to its ability to engage participants while providing intensive training with feedback and reinforcement. Perhaps surprisingly, positive feedback can facilitate learning even when it is random in relation to a listener's responses, although excessive feedback (e.g., on 90% of trials) or no feedback at all does not contribute to learning.[45] Thus, feedback given intermittently appears to be more effective at encouraging learning than feedback given more frequently.[45,46] Motivation is related to attention. The greater the attention to a given task (such as AT), the more progress is likely to be made, and higher levels of vigilance can be maintained when the individual involved is motivated compared with unmotivated individuals.[47] Moreover, top-down processes such as arousal and attention aid perceptual or sensory learning.[40,45,48,49]

Transfer of Learning

The question as to whether AT-induced learning transfers to auditory stimuli and auditory skills not used in the training paradigm is a popular topic in AT research. As clinicians, this is a topic of significant relevance as we assume that, to some degree, administration of AT will benefit the auditory system more generally and not just for the stimuli applied. It is important for the clinician who is administering AT to consider to what degree the therapy improves outcomes that do not utilize the exact stimuli that were employed during AT (i.e., what degree of transfer of learning occurred).

Transfer of learning has been investigated within-task, that is, how well stimulus training transfers to another stimulus of a similar type for the same task, and between-task, or how well stimulus training transfers to a completely different type of auditory task that utilizes much different stimuli. Studies investigating within-task transfer effects have often examined how well training using one stimulus transfers to performance using another stimulus that has a slightly different acoustic characteristic from the first. Training participants on a duration discrimination task has been shown to generalize to improvements for stimuli with durations not used during the training.[50] Similarly, training on a frequency discrimination task also tends to generalize to frequencies not used during the training, at least after several administrations of the untrained frequencies.[51]

Research examining between-task transfer effects have frequently addressed to what degree training on basic auditory processing tasks transfers to more complex skills. For instance, Kujala et al examined whether a combined nonspeech temporal processing and auditory discrimination AT would generalize to skills like reading.[52] They noted that the trained group showed a significant increase in the number of words and the reading rate. Moore et al trained participants on a phoneme discrimination task and examined to what degree this training generalized to receptive language skills.[53] They noted that, as a group, phonological awareness and word discrimination scores did improve following training.

There certainly are situations, however, in which transfer of learning does not appear to occur. Millward and colleagues trained participants on either a frequency discrimination task in quiet or in the presence of modulated noise, or on words in modulated noise.[54] All trained groups, and even a control group that was untrained, showed some improvements on a words-in-noise probe; however, frequency discrimination improvements were seen only in subjects who were included in one of the frequency discrimination training groups. The authors concluded that, in general, if the training stimulus shares some dimension with the outcome measure, then training benefits are more likely to be seen. This conclusion was supported by further research showing that learning does not always generalize across stimuli or tasks.[55]

Transfer of learning, when it occurs, almost certainly makes use of nonauditory specific skills (i.e., supramodal skills) or what others have called procedural or conceptual learning.[56,57] Delhommeau et al discussed transfer of learning in the context of meta-learning, or learning about the basic nature of the AT task.[51] Learning in this way would be expected to recruit cognitive skills that contribute to within-task transfer of learning. Moore et al also emphasized the benefits that AT provides to attention and how these improvements in attention could facilitate transfer of learning to tasks and skills not applied during the training paradigm.[53] Evidence from this viewpoint is provided by research that has shown that training on a visual task (which does not recruit the auditory system at all) can lead to improvements in auditory discrimination.[40]

Process-Specific Training

A related concept is what has been called "process-specific training." It has been recommended that AT be process-specific when administered to patients with CAPD. That is, the auditory process(es) shown to be deficient should be targeted in AT.[6] To perform process-specific training, a full CAPD diagnostic evaluation must be completed prior to undertaking AT with older children (i.e., age 7 to 8 years and older) and adults. The diagnostic test battery should provide information about the patient's particular auditory strengths and weaknesses. As many clinics that perform CAP evaluations today do not test a full range of central auditory capabilities (e.g., dichotic processing, temporal processing, perception of monaural low redundancy speech, and binaural interaction),[14] an incomplete profile of the patient's auditory strengths and weaknesses is often generated, making it difficult to decide precisely what skills to train.[58] Research is not available regarding the considerations that actually guide clinicians' specific decisions when creating a CAPD test battery, although it is frequently recommended that sensitivity and specificity data from CAPD tests and test batteries be prioritized in this context.[4]

REVIEW OF AUDITORY TRAINING RESEARCH PERFORMED ON PARTICIPANTS WITH AUDITORY COMPLAINTS

Although there is a fairly large body of research investigating AT (or auditory-language training) in children with speech-language and/or learning disabilities, very few studies have examined the effectiveness of AT in children diagnosed with CAPD or some form of nonperipheral auditory deficit. Studies that look at training-based remediation in individuals with auditory complaints are important for a variety of reasons. Foremost among these is that such studies speak specifically to whether these paradigms benefit the very individuals toward which these therapies are targeted. To this end, the present section provides a more detailed discussion of those research studies that have examined AT in individuals with primarily auditory complaints.

Each of the studies below is considered from the perspective of the level of evidence that applies. Using terminology reported in Appendix A of the American Academy of Audiology (AAA) CAPD practice guidelines, level 1 includes the most rigorous studies (e.g., double-blind, randomized clinical trials, etc.), level 2 includes quasi-experimental research (e.g., nonrandomized, retrospective designs with control groups, etc.), level 3 includes observational studies with controls (e.g., case studies, cohort studies, etc.), level 4 includes descriptive studies (i.e., observational without controls), and level 5 reflects expert clinical opinion, consensus, or standards for practice.[6] Each of the studies discussed below are listed in Table 1 along with the respective level of evidence. In some cases, the classification into level of evidence is imperfect given that the research did not exactly fit the definition for any level. In these cases, the level that best described the research was selected.

Temporal Processing Training and Auditory Discrimination Training

Temporal processing represents a broad category of auditory processes, including skills such as temporal sequencing, temporal integration, temporal resolution, and others. Additional skills that are fundamental to temporal processing are frequency, intensity, and duration discrimination.[59] AT paradigms that target temporal processing are generally varied in their focus and scope given the range of temporal

Table 1 Levels of Evidence for Studies Investigating the Efficacy of AT in Patients with Auditory Complaints

Study	Level of Evidence*
Sharma et al[60]	1
Krishnamurti et al[61]	4
McArthur et al[59]	4
Moncrieff and Wertz[68]	4
Musiek et al[26]	4
Weihing et al[70]	3
Cameron and Dillon[29]	4
Musiek and Schochat[25]	4
Putter-Katz et al[74]	2
Alonso and Schochat[75]	4
Schochat et al[76]	2
Musiek and Baran[77]	4
Musiek et al[78]	4
Musiek et al[79]	4

Note: Studies are listed in the order that they are cited in the text.

*Level 1: most rigorous studies (e.g., double blind, randomized clinical trials, etc.); level 2: quasi-experimental research (e.g., non-randomized, retrospective designs with control groups, etc.); level 3: observational studies with controls (e.g., case studies, cohort studies, etc.); level 4: descriptive studies (i.e., observational without controls), and level 5 reflects expert clinical opinion, consensus, or standards for practice.[6]

processes that can be addressed. Some of these paradigms are considered next.

Sharma et al recruited 55 children (7 to 13 years, mean = 9.7 years) who were diagnosed with CAPD according to the AAA guidelines.[60] Subjects all had normal peripheral hearing sensitivity and were randomly assigned to one of the following conditions: auditory discrimination training (AT), auditory discrimination training and FM system, language therapy, language therapy and FM system, or a nonintervention control group. Training entailed a total of 12 hours of intervention that included both home-based and clinic-based tasks. The 5-week training consisted of 1-hour clinical sessions weekly and 15 minutes of exercises at home for 5 days a week. The exercises performed at home consisted of some of the AT games included in Earobics, in particular the tasks that focused on phonological training. For the language therapy group, home exercises consisted of the following: reading aloud while emphasizing correct stress and intonation, and focusing on appreciating differences in meaning that are conveyed from the use of different stress and timing patterns. The findings indicated that all interventions yielded some degree of improvement. Both the auditory discrimination training and the language therapy groups showed posttraining improvements in temporal processing. These groups showed additional benefits in language and reading outcomes. Although these results might suggest that either AT or language therapy can yield the same results, it is generally expected that training that specifically focuses on an affected auditory process(es) will most likely produce greatest benefits, as described earlier. Because the AT paradigm did not necessarily address processes shown to be affected by the CAPD test battery, lesser gains might have shown by these participants than if a process-specific AT approach had been adopted. It should be noted that a control group that did not receive any interventions did not show significant improvement on measures over time.

Krishnamurti et al examined the effectiveness of FFW in two cases diagnosed with CAPD. As noted earlier, FFW is a computer-based AT paradigm that targets temporal processing and auditory discrimination skills in a speech-language context.[61] The two pediatric cases (7 to 8 years old) presented normal peripheral hearing sensitivity and showed difficulties on the researchers' central auditory test battery. The battery consisted of one highly sensitive and specific nonverbal measure of CAPD[4] (i.e., Frequency Patterns[11]), as well as several auditory language-based measures that more generally involve central auditory aspects as well (i.e., SCAN-C,[62] Phonemic Synthesis,[63] and TAPS-R[64]). The children also were administered measures to look at an electrophysiologic measure of auditory processing, as well as language or more general supramodal skills. These measures included the Test of Nonverbal Intelligence (TONI),[65] Clinical Evaluation of Language Fundamentals (CELF),[66] and the speech auditory brainstem response (seABR).[67] The children participated in this AT paradigm over an 8- to 12-week period, 5 days a week, for 50-minute sessions.

Results showed that the first participant improved on the FFW tasks, which was expected given the intensity of the training. This participant also demonstrated gains on the SCAN, Frequency Patterns, Phonemic Synthesis, and the CELF. Benefits seemed to generalize beyond the central auditory and language measures, as indicated by improvements in cognition as measured by the TONI. Improvements also were observed electrophysiologically on the seABR, which was seen as an increase in amplitude of the V-A response (i.e., peak-to-peak amplitude from wave V to the negativity that follows wave V). The second participant showed similar improvements following training on the auditory processing measures and the seABR (i.e., shorter latencies); however, no notable improvements were seen on the TONI or the CELF. These findings should be interpreted with caution as they reflect the results of only two subjects.

McArthur and coworkers recruited 28 children (6 to 15 years old) who presented with a specific reading disability or a specific language impairment and who also demonstrated below-normal performance on temporal processing measures.[59] Although a CAPD battery was not administered, the reduced performance on tests of temporal processing indicated this sample experienced difficulties on auditory processing tasks. Children were trained on one of the following auditory discrimination or temporal processing tasks: frequency discrimination, vowel discrimination, consonant–vowel discrimination, or backward masking. Training, which was designed to be adaptive in difficulty, was administered for 30 minutes a day, 4 days a week, for 6 weeks. Psychoacoustic tasks that were similar to the AT exercises were administered before the AT paradigm was started and then a second time following the last training session. Approximately 90% of the participants demonstrated performance on these measures that was within normal limits following the last training session. The improvements shown did not appear to be explained by a more global change in how participants approached the tasks. This was evidenced by the finding that participants did not show improvements for two nonauditory tasks: visual discrimination and sustained attention tasks. Additionally, subjects in a control condition who were not exposed to the training also demonstrated some degree of improvement on outcome measures when administered at retest; however, the magnitudes of these improvements were smaller than that seen from the trained group. Of note was that the control participants generally demonstrated better temporal processing skills than the trained group when measured at the pretraining session and, therefore, did not have as much potential for improvement as the experimental group.

Dichotic Auditory Training

Several studies have examined the effectiveness of dichotic training in participants with dichotic processing issues as confirmed using CAPD tests. Moncrieff and Wertz administered dichotic therapy ("Auditory Rehabilitation for Interaural Asymmetry") to children with dichotic deficits in two studies.[68] The dichotic issues exhibited by the participants were either a unilateral left ear weakness or a bilateral weakness. In both studies, dichotic stimuli were presented through two speakers in the sound field, and difficulty was adjusted by increasing the intensity of the acoustic signal coming from the right speaker over time. The initial interaural intensity difference was 30 dB; as patients gradually demonstrated an improvement in performance, this interaural intensity difference was decreased across sessions by 1 to 5 dB to maintain performance between 70 and 100%. Eight children ranging in age between 7 and 13 years participated in the first study reported by Moncrieff and Wertz. The children trained for 30 minutes per session, three sessions a week, for 4 weeks. This study represented a phase I and phase II clinical trials in which a treatment is investigated in a smaller and then larger group of participants, respectively, to examine the treatment's ability to yield improvements on outcomes. Control groups were not included as part of the phase I and phase II clinical trials.

Findings indicated that left ear performance for dichotic digits improved significantly following training, with the average observed improvement of ~15%. In their second study, Moncrieff and Wertz recruited a larger sample of children (6.5 to 11 years, $n = 13$).[68] In addition to a larger sample, some participants in study 2 trained over a longer duration (ranging from 12 to 24 sessions), and they were also given additional nondichotic listening comprehension outcome measures to assess the generalization of benefits. In this second study, significant left and right ear improvements posttraining were seen for both dichotic digits and competing words measures, with an approximate 20% improvement in performance for the left ear. Although improvements in the right ear were much smaller in magnitude, pretraining performance for the right ear generally was much higher than the left ear score, which limited the degree of improvement that could obtained. This observation relates to a common trend seen in AT studies where individuals with poorer baseline performance generally obtain greater gains from AT.[32,60,69] A significant correlation was obtained between improvements in left ear scores on both dichotic measures and the listening comprehension measures (i.e., Brigance Comprehensive Inventory of Basic Skills Revised).

Musiek et al reported AT data in which a DIID-like therapy was administered to 14 children with dichotic issues for 10 weeks.[26] Although the paradigm typically attempts to improve weaker ear performance by manipulating interaural level differences, this study utilized interaural timing differences instead. The authors referred to this variant of the DIID paradigm as the DIID II. By having the stimulus in the weaker ear arrive slightly later in time than the stimulus in the better ear, the weaker ear obtains a dichotic processing advantage (i.e., the lag effect). As the patient improves over time, the lag between the ears is gradually decreased to make the task more challenging. In this particular study, no control group was recruited.

The authors reported a significant improvement in pre- versus posttraining dichotic listening scores that was ~30% in magnitude. Interestingly, improvements in dichotic processing also appeared to be related to a reduction of everyday symptoms, as determined by parent or teacher report. Questionnaire respondents were asked about the patient's improvements in their ability to follow directions, communication ability, academic performance, attention, and ability to hear in noise. Scores ranged from 0 (no improvement) to 5 (100% improvement). Examined collectively, the trained group demonstrated average or greater than average improvement.

Weihing et al administered the DIID to four older adults, two who demonstrated dichotic deficits and two who showed normal dichotic processing.[70] The DIID was performed over ~20 sessions using a range of stimuli and instructions. Following the termination of training, adults with dichotic deficits showed improvement and, in some cases, normal dichotic processing. Furthermore, the subjects with dichotic deficits showed improved performance on the Quick-SIN posttraining, and those without deficits did not improve on this measure as much. These initial results are encouraging, suggesting the utility of the DIID to patients with central presbycusis. The findings must be tempered, however, by the small sample size and the fact that the older adults without dichotic deficits were younger by ~8 years and showed better peripheral hearing than the older adults with dichotic deficits.

Spatial Processing

As mentioned above, the LiSN and Learn was developed to treat spatial processing disorder.[29] To evaluate the utility of this approach, Cameron and Dillon enrolled nine children (6 to 11 years) to participate in the LiSN and Learn program, 15 to 20 minutes a day, five times a week, for ~3 months.[29] Results revealed that participants were better able to make use of spatial separation cues following training and that these improvements persisted 3 months posttraining. Significant benefits were also noted on some measures of attention and memory, as well as on report measures of hearing handicap. Although LiSN and Learn appears to provide benefits to children with this type of processing issue when they have normal peripheral hearing, the training does not appear to be as effective in cases of sensorineural hearing loss.[71]

Battery Approach to Training

Several studies have investigated whether a battery of treatment approaches for individuals diagnosed with CAPD or auditory complaints provides benefits to this clinical group. The training battery approach includes multiple types of AT exercises, spanning a range of auditory processes, and may also make use of top-down instruction and compensatory modifications. Although the training battery approach described below does not always target processes that were shown to be deficient, this approach has some ecological validity as individuals with CAPD typically present with issues related to more than one auditory process or ability. Moreover, difficulties with multiple auditory processes are frequently thought to underlie listening deficits (e.g., listening difficulty in noise might be due to binaural separation issues, spatial processing issues, temporal processing issues, etc.). Thus, a training battery approach may be beneficial when the affected auditory process cannot be easily identified or isolated. This might occur, for instance, if electrophysiologic measures were used to diagnosis an auditory processing deficit.

Musiek and Schochat reported a case study in which a 15-year-old with CAPD received benefits from an AT battery.[25] Diagnosis of CAPD was made using four tests: Dichotic

Digits,[9] Compressed Speech,[72] Frequency Patterns,[11] and Duration Patterns.[73] Prior to training, the child showed difficulties on all of the CAPD measures with the exception of the Duration Patterns. The clinical AT protocol followed a schedule of 1-hour sessions, three times a week, for 6 weeks. Additional exercises also were provided informally so that participants could engage in therapy at home. These informal exercises were completed for 15 to 30 minutes, two to three times a week. Formal training tasks provided in the clinic focused on auditory discrimination (i.e., intensity discrimination, frequency discrimination, CV discrimination), dichotic processing (i.e., DIID training), and monaural low-redundancy (i.e., speech-in-noise training). Difficulty level of these tasks was adaptive to maintain performance at 70% correct. Informal training tasks performed at home included such tasks as reading aloud with good intonation and rhythm (which is a top-down approach that targets discrimination and temporal processing) and identification of target lyrics in songs.

When the training paradigm was completed, the participant had improved or attained normal CAP, particularly for the compressed speech task and dichotic processing measures. The participant's parent completed a hearing questionnaire that targeted the degree of improvement received from the training, rated from 0 (no improvement) to 5 (no longer has a problem in this area). Target behaviors included following directions, communication ability, academic ability, attention span, ability to recognize speech recognition in noise, and alertness. The parent indicated that the participant showed considerable (score of 3) to marked improvement (score of 4) in these areas. The range of areas in which improvements were noted following training may speak to the broad scope of the skills targeted in this AT paradigm and/or to the primacy of CAPD in contributing to the patient's symptoms.

Putter-Katz and colleagues used dichotic listening and speech-in-noise tasks in an AT paradigm and coupled this approach with the fitting of an FM system, in addition to top-down interventions (e.g., modification of learning strategies, cognitive and metacognitive approaches, and classroom and home modifications).[74] Participants included 20 children, ranging in age from 7 to 14 years (mean = 9 years), and 10 control subjects who ranged in age from 6 to 11 years (mean = 8 years). The control subjects received neither training nor intervention. Both groups were diagnosed with CAPD based on the following criteria: performance below 1 standard deviation in at least one ear on one or more of the central auditory tests used in the study. These central auditory tests included dichotic listening (binaural separation), monaural low-redundancy, temporal processing (i.e., gap detection ability), and binaural interaction. All participants presented with listening difficulties, as noted by caregivers, parents, and teachers. Examination of the types of deficits seen in this group revealed that 11 children were diagnosed with monaural low-redundancy deficits only (i.e., "noise group"), and 9 children were diagnosed with deficits on tests that assess monaural low-redundancy speech perception and dichotic processing skills (i.e., "noise + dichotic group"). A training paradigm was administered for 45 minutes, once a week, for 4 months. Outcome measures included the central auditory tests administered prior to training. Following 4 months of training, central auditory test scores increased for participants in both the "noise" and "noise + dichotic" groups. The control group did not show similar improvements.

Alonso and Schochat recruited 29 children with CAPD who ranged in age from 8 to 16 years to determine the utility of AT.[75] The diagnostic CAPD battery included two measures of monaural low-redundancy and two measures of dichotic processing. The CAPD diagnosis was made based on the participant failing at least two CAPD tests in the battery. These tests and the auditory P300 served as outcome measures for the study. The training schedule consisted of eight, 50-minute sessions, once per week for 8 weeks. The training paradigm was similar to that employed by Musiek and Schochat (described above).[25] Task difficulty was modified each week to maintain performance at ~70%. At the end of the training, significant improvements were observed on most of the outcome measures, including P300 latency and all CAPD tests.

Nearly 73% of the participants presented normal auditory processing ability following training.

Schochat et al recruited 30 children with CAPD and 22 without CAPD for an AT study.[76] Participants ranged in age from 8 to 14 years and were diagnosed with CAPD using the criteria set forth by American Speech-Language-Hearing Association and AAA.[6,30] None of the participants was diagnosed with peripheral hearing loss. The children diagnosed with CAPD were enrolled in training for 8 weeks, with 50-minute sessions, once weekly. Training tasks were comprised of a combination of frequency discrimination, intensity discrimination, duration discrimination, gap detection, DIID, localization, and speech perception training. Informal exercises consisted of word recognition tasks that were given to subjects to be completed at home for 15 minutes daily. Posttraining outcome measures consisted of speech recognition in quiet and in noise, verbal and nonverbal dichotic listening, and the auditory middle latency response. Participants exhibited significant improvement on all central auditory tests following training. Additionally, the children who received training also showed an increase in the amplitude of the middle latency response when it was measured over the left hemisphere. This electrophysiologic enhancement was not seen in the control group.

Several case studies with patients with neurologic symptoms also have examined the effectiveness of AT using a battery of auditory exercises and interventions. Musiek and Baran reported on a young adult patient who experienced a hemorrhage in the pons that was a consequence of an arteriovenous malformation.[77] The patient was evaluated audiologically at 3 months following this event, at which point she had noted significant hearing difficulties, especially when listening in background noise. An audiogram performed at this visit showed relatively normal hearing in the left ear and a sensorineural loss that was severe in the high frequencies in the right ear. Two monaural low-redundancy tests also were administered. Performance on these tests was 0% in the right ear and ranged between 50 and 75% in the left ear. The patient was enrolled in an informal rehabilitation protocol, which included the following recommendations: wear an earplug in the right ear to prevent distortion, use an assistive listening device, and participate in AT. The patient was enrolled in AT for ~15 to 20 minutes daily for 6 months. AT consisted of auditory discrimination of numbers, consonants, vowels, words, and sentences. These tasks were administered over the telephone (to simulate a monaural low-redundancy, filtered speech context) with a friend reading the stimuli to the patient. During each AT session, training began with the better ear and then proceeded to the poorer right ear. Her performance on CAPD tests was reassessed twice during the course of training. Subjectively, the patient noted significant improvements in listening, although listening in noisy situations was still challenging. Her right ear performance on one of the monaural low-redundancy tests demonstrated improvement, from 0 to ~50%. Interestingly, the high-frequency sensorineural hearing loss also showed improvement, progressing from a severe loss to mild to moderate loss. It should be noted though that this improvement was likely seen because a portion of her hearing loss was related to central changes that may have been coincident with the hemorrhage in her pons. In general, it would not be expected that AT would improve peripheral hearing loss.

In another case, Musiek and coworkers reported on a 21-year-old patient with a subarachnoid bleed that involved the inferior colliculi bilaterally.[78] Initially, the patient showed a complete central hearing loss and was unresponsive to sounds. Physiologic measures showed normal otoacoustic emissions and auditory brainstem response through wave III. Over the course of 12 weeks, improvements were seen in his hearing sensitivity, and by 10 months his hearing sensitivity was equivalent to a moderately severe hearing loss. The patient continued to experience difficulties hearing in noise even though his hearing sensitivity had improved. Intensity discrimination was measured at 5 and 11 weeks postinsult. At both sessions, the difference limen to intensity was elevated, though it was slightly improved at 11 weeks for the right ear and for binaural administration. Electrophysiologic measures, including the middle latency response and event-related potentials, were also abnormal, further confirming involvement of the central auditory system. An auditory treatment plan was put into place 1 month after the patient left the hospital. The AT paradigm was administered formally, once a week for approximately an hour, for 14 weeks. Training was adaptive to maintain difficulty at a moderate level. Additionally, informal exercises were given for home use and these included auditory directives, discrimination tasks, and music listening. Initially, the formal training consisted of the following: having the patient answer questions about himself, administration of discrimination tasks, and speech reading. When the treatment paradigm was ~50% complete, the therapy focus changed to identification and discrimination of voices and environmental sounds, speech recognition in noise, identification of nonword speech sounds, and reading aloud. The patient made clear progress in auditory discrimination ability throughout these latter stages of therapy. Toward the end of treatment, an emphasis was placed on significantly increasing the difficulty of therapy because the patient had, to this point, shown large gains in performance. Discrimination tasks included sounds that were more similar, and more complex sentence-level material was introduced. An assistive listening device also was dispensed around this time. It should be noted that Musiek et al acknowledged it was difficult to separate out benefits obtained from AT from those obtained from spontaneous recovery.[78]

Musiek and colleagues also reported an AT case in which hearing difficulties were noted following a mild head trauma.[79] The 41-year-old patient reported difficulty attending for longer periods of time, especially when auditory information was presented. She also observed difficulty understanding multistep directions and felt she had more difficulty hearing from the left ear than the right ear, despite showing normal and symmetrical hearing sensitivity bilaterally. A CAPD evaluation that included Dichotic Digits, Competing Sentences, Frequency Patterns, Duration Patterns, and Compressed Speech revealed that the patient's performance was consistent with a diagnosis of CAPD. She was enrolled in an AT program that included training in advocating for clear speech, reading aloud, DIID training, auditory memory enhancement training, auditory speech discrimination training, temporal sequence training, and instruction on metacognitive strategies. Posttraining, the patient showed significant gains in CAP: performance on the dichotic digits and right ear scores on the compressed speech and competing sentences were now within normal limits. Significant improvements also were seen in the left ear on compressed speech and competing sentences, though performance only bordered normal limits.

CONCLUSIONS

The present article has described AT approaches for the treatment of CAPD. Training focused on one or more auditory processes, including temporal processes, dichotic processing, perception of monaurally presented low-redundancy signals, and binaural interaction, including the related spatial processing. Several AT (and auditory-language) exercises are available for administration via the computer (i.e., CBAT). CBAT has many advantages over face-to-face training, including controlled presentation of stimuli, precise implementation of adaptive difficulty, intensiveness (i.e., number of trials per session), and engaging and reinforcing interfaces. Characteristics of successful AT include application of appropriate training schedules, use of adaptive difficulty, and presentation of reinforcement to maintain motivation. Transfer of learning is known to occur, though the magnitude of the transfer effect is larger for tasks that are more similar to the trained task. Although published research generally shows a positive impact of AT in this population, future CAPD training research should strive to include control groups (or control as well as target dependent variables in single-subject research) wherever possible and focus on the degree to which benefits generalize to listening skills not trained during the AT paradigm. The skills assessed should be related to the presenting symptoms of patients with CAPD, such as difficulty hearing in noise, and might be measured using behavioral and electrophysiologic measures, well as validated, informant (e.g., parent) report measures. Additionally, future research should be designed to be more consistent with phase III clinical trials in which control groups are generally recruited. Finally, it is often recommended that AT take a process-specific approach, in which the processes shown to be affected by CAPD are targeted by the training paradigm. At this time, the scientific literature does not establish that this approach yields larger gains than a more general training protocol (e.g., AT training battery), which is not necessarily process specific.

REFERENCES

1. Musiek F, Gollegly K, Baran J. Myelination of the corpus callosum and auditory processing problems. Semin Hear 1984;5:231–240
2. Boscariol M, Garcia VL, Guimarães CA, et al. Auditory processing disorder in perisylvian syndrome. Brain Dev 2010;32(4):299–304
3. Boscariol M, Guimarães CA, Hage SR, et al. Auditory processing disorder in patients with language-learning impairment and correlation with malformation of cortical development. Brain Dev 2011;33(10):824–831
4. Musiek FE, Chermak GD, Weihing J, Zappulla M, Nagle S. Diagnostic accuracy of established central auditory processing test batteries in patients with documented brain lesions. J Am Acad Audiol 2011;22(6):342–358
5. Gates GA. Central presbycusis: an emerging view. Otolaryngol Head Neck Surg 2012;147(1):1–2
6. American Academy of Audiology. Diagnosis, treatment and management of children and adults with central auditory processing disorder. Available at: http://audiology-web.s3.amazonaws.com/migrated/CAPD%20Guidelines%208-2010.pdf_539952af956c79.73897613.pdf. September 14, 2015
7. Chermak G, Musiek F. Central Auditory Processing Disorders: New Perspectives. San Diego, CA: Singular Publishing Group; 1997
8. Chermak G, Musiek F. Psychophysical and behavioral peripheral and central auditory tests. In: Celesia G, Hickok G, eds. Handbook of Clinical Neurology: The Human Auditory System: Fundamental Organization and Clinical Disorders. Amsterdam, The Netherlands: Elsevier; 2015
9. Musiek FE. Assessment of central auditory dysfunction: the dichotic digit test revisited. Ear Hear 1983;4(2):79–83
10. Willeford J, Burleigh J. Sentence procedures in central testing. In: Handbook of Clinical Audiology; Philadelphia, PA: Lippincott Williams & Wilkins; 1994
11. Musiek FE, Pinheiro ML. Frequency patterns in cochlear, brainstem, and cerebral lesions. Audiology 1987;26(2):79–88
12. Musiek FE, Shinn JB, Jirsa R, Bamiou DE, Baran JA, Zaida E. GIN (Gaps-In-Noise) test performance in subjects with confirmed central auditory nervous system involvement. Ear Hear 2005;26(6):608–618
13. Willeford J. Differential diagnosis of central auditory dysfunction. In: Bradford L, ed. Audiology: An Audio Journal for Continuing Education. New York, NY: Grune and Stratton; 1976
14. Emanuel DC, Ficca KN, Korczak P. Survey of the diagnosis and management of auditory processing disorder. Am J Audiol 2011;20(1):48–60
15. Wilson RH, Zizz CA, Sperry JL. Masking-level difference for spondaic words in 2000-msec bursts of broadband noise. J Am Acad Audiol 1994;5(4):236–242
16. Cameron S, Dillon H, Newall P. Development and evaluation of the listening in spatialized noise test. Ear Hear 2006;27(1):30–42
17. Musiek FE, Baran JA, Schochat E. Selected management approaches to central auditory processing disorders. Scand Audiol Suppl 1999;51:63–76
18. Thibodeau L. Computer-based auditory training (CBAT) for central auditory processing disorder. In: Chermak G, Musiek F, eds. Handbook of Central Auditory Processing Disorder Volume 2: Comprehensive Intervention. San Diego, CA: Plural Publishing; 2014
19. Musiek F, Chermak G, Weihing J. Auditory Training. In: Chermak G, Musiek F, eds. Handbook of Central Auditory Processing Disorder Volume 2: Comprehensive Intervention. San Diego, CA: Plural Publishing; 2014
20. Loo JH, Bamiou DE, Campbell N, Luxon LM. Computer-based auditory training (CBAT): benefits for children with language- and reading-related learning difficulties. Dev Med Child Neurol 2010;52(8):708–717
21. Russo NM, Nicol TG, Zecker SG, Hayes EA, Kraus N. Auditory training improves neural timing in the human brainstem. Behav Brain Res 2005;156(1):95–103
22. Warrier CM, Johnson KL, Hayes EA, Nicol T, Kraus N. Learning impaired children exhibit timing deficits and training-related improvements in auditory cortical responses to speech in noise. Exp Brain Res 2004;157(4):431–441
23. Tallal P, Miller SL, Bedi G, et al. Language comprehension in language-learning impaired children improved with acoustically modified speech. Science 1996;271(5245):81–84
24. Merzenich MM, Jenkins WM, Johnston P, Schreiner C, Miller SL, Tallal P. Temporal processing deficits of language-learning impaired

children ameliorated by training. Science 1996; 271(5245):77–81
25. Musiek F, Schochat E. Auditory training and central auditory processing disorders: a case study. Semin Hear 1998;19:357–365
26. Musiek F, Weihing J, Lau C. Dichotic interaural intensity difference (DIID) training: a review of existing research and future directions. J Acad Reh 2008;41:51–65
27. Chermak G, Weihing J, Musiek F. Sound Auditory Training for Central Auditory Processing Disorder. Paper present at: AudiologyNow Conference; 2015; San Antonio, TX
28. Weihing J, Musiek F. Dichotic interaural intensity difference (DIID) training. In: Chermak G, Musiek F, eds. Handbook of Central Auditory Processing Disorder Volume 2: Comprehensive Intervention. San Diego, CA: Plural Publishing; 2014
29. Cameron S, Dillon H. Development and evaluation of the LiSN & learn auditory training software for deficit-specific remediation of binaural processing deficits in children: preliminary findings. J Am Acad Audiol 2011;22(10):678–696
30. American Speech-Language-Hearing Association. (Central) auditory processing disorders—technical report. Available at: http://www.asha.org/policy/TR2005-00043/. Accessed September 14, 2015
31. Molloy K, Moore DR, Sohoglu E, Amitay S. Less is more: latent learning is maximized by shorter training sessions in auditory perceptual learning. PLoS ONE 2012;7(5):e36929
32. Amitay S, Hawkey DJ, Moore DR. Auditory frequency discrimination learning is affected by stimulus variability. Percept Psychophys 2005; 67(4):691–698
33. Hawkey DJ, Amitay S, Moore DR. Early and rapid perceptual learning. Nat Neurosci 2004;7(10): 1055–1056
34. Tremblay K, Kraus N, McGee T. The time course of auditory perceptual learning: neurophysiological changes during speech-sound training. Neuroreport 1998;9(16):3557–3560
35. Anderson S, White-Schwoch T, Choi HJ, Kraus N. Partial maintenance of auditory-based cognitive training benefits in older adults. Neuropsychologia 2014;62:286–296
36. Sampayo-Vargas S, Cope C, He Z, Byrne G. The effectiveness of adaptive difficulty adjustments on students' motivation and learning in an educational computer game. Comput Educ 2013; 69:452–462
37. Chermak G, Musiek F. Auditory training: principles and approaches for remediating and managing auditory processing disorders. Semin Hear 2002; 23:297–308
38. Erber N. Auditory Training. Washington DC: Graham Bell Association for the Deaf; 1982
39. Linkenhoker BA, Knudsen EI. Incremental training increases the plasticity of the auditory space map in adult barn owls. Nature 2002;419(6904): 293–296
40. Amitay S, Irwin A, Moore DR. Discrimination learning induced by training with identical stimuli. Nat Neurosci 2006;9(11):1446–1448
41. Roth DA, Refael-Taub R, Sharvit R, Kishon-Rabin L. Can learning a frequency discrimination task occur without discrimination? J Basic Clin Physiol Pharmacol 2006;17(3):159–171
42. Edeline JM, Pham P, Weinberger NM. Rapid development of learning-induced receptive field plasticity in the auditory cortex. Behav Neurosci 1993;107(4):539–551
43. Reagan C. Handbook of Auditory Perceptual Training. Springfield, IL: Charles C Thomas; 1973
44. Danzl MM, Etter NM, Andreatta RD, Kitzman PH. Facilitating neurorehabilitation through principles of engagement. J Allied Health 2012;41(1): 35–41
45. Amitay S, Halliday L, Taylor J, Sohoglu E, Moore DR. Motivation and intelligence drive auditory perceptual learning. PLoS ONE 2010;5(3):e9816
46. Kendall SB. Preference for intermittent reinforcement. J Exp Anal Behav 1974;21(3):463–473
47. Tomporowski PD, Tinsley VF. Effects of memory demand and motivation on sustained attention in young and older adults. Am J Psychol 1996;109(2): 187–204
48. Alain C, Campeanu S, Tremblay K. Changes in sensory evoked responses coincide with rapid improvement in speech identification performance. J Cogn Neurosci 2010;22(2):392–403
49. Halliday LF, Moore DR, Taylor JL, Amitay S. Dimension-specific attention directs learning and listening on auditory training tasks. Atten Percept Psychophys 2011;73(5):1329–1335
50. Delhommeau K, Micheyl C, Jouvent R, Collet L. Transfer of learning across durations and ears in auditory frequency discrimination. Percept Psychophys 2002;64(3):426–436
51. Delhommeau K, Micheyl C, Jouvent R. Generalization of frequency discrimination learning across frequencies and ears: implications for underlying neural mechanisms in humans. J Assoc Res Otolaryngol 2005;6(2):171–179
52. Kujala T, Karma K, Ceponiene R, et al. Plastic neural changes and reading improvement caused by audiovisual training in reading-impaired children. Proc Natl Acad Sci U S A 2001;98(18): 10509–10514
53. Moore DR, Rosenberg JF, Coleman JS. Discrimination training of phonemic contrasts enhances phonological processing in mainstream school children. Brain Lang 2005;94(1):72–85
54. Millward KE, Hall RL, Ferguson MA, Moore DR. Training speech-in-noise perception in

mainstream school children. Int J Pediatr Otorhinolaryngol 2011;75(11):1408–1417

55. Halliday LF, Taylor JL, Millward KE, Moore DR. Lack of generalization of auditory learning in typically developing children. J Speech Lang Hear Res 2012;55(1):168–181
56. Ortiz JA, Wright BA. Differential rates of consolidation of conceptual and stimulus learning following training on an auditory skill. Exp Brain Res 2010;201(3):441–451
57. Wright BA, Fitzgerald MB. Different patterns of human discrimination learning for two interaural cues to sound-source location. Proc Natl Acad Sci U S A 2001;98(21):12307–12312
58. Chermak GD, Silva ME, Nye J, Hasbrouck J, Musiek FE. An update on professional education and clinical practices in central auditory processing. J Am Acad Audiol 2007;18(5):428–452, quiz 455
59. McArthur GM, Ellis D, Atkinson CM, Coltheart M. Auditory processing deficits in children with reading and language impairments: can they (and should they) be treated? Cognition 2008;107(3): 946–977
60. Sharma M, Purdy SC, Kelly AS. A randomized control trial of interventions in school-aged children with auditory processing disorders. Int J Audiol 2012;51(7):506–518
61. Krishnamurti S, Forrester J, Rutledge C, Holmes GW. A case study of the changes in the speech-evoked auditory brainstem response associated with auditory training in children with auditory processing disorders. Int J Pediatr Otorhinolaryngol 2013;77(4):594–604
62. Keith RW. Development and standardization of SCAN-C test for auditory processing disorders in children. J Am Acad Audiol 2000;11(8):438–445
63. Katz J, Medol E. The use of phonemic synthesis in speech therapy. Menorah Med J 1971;3:10–13
64. Martin N, Brownell R. Test of Auditory Processing Skills. Novato CA: Academic Therapy; 2005
65. Brown L, Sherbenou R, Johnsen S. Test of Nonverbal Intelligence: A Language-Free Measure of Cognitive Ability. Austin, TX: Pro-ed; 1990
66. Semel E, Wiig E, Secord W. CELF 3, Clinical Evaluation of Language Fundamentals: Observational Rating Scales. San Antonio, TX: Psychological Corporation; 1996
67. Wong PC, Skoe E, Russo NM, Dees T, Kraus N. Musical experience shapes human brainstem encoding of linguistic pitch patterns. Nat Neurosci 2007;10(4):420–422
68. Moncrieff DW, Wertz D. Auditory rehabilitation for interaural asymmetry: preliminary evidence of improved dichotic listening performance following intensive training. Int J Audiol 2008;47(2):84–97
69. Lakshminarayanan K, Tallal P. Generalization of non-linguistic auditory perceptual training to syllable discrimination. Restor Neurol Neurosci 2007; 25(3-4):263–272
70. Weihing J, Shinn J, Preminger J, Khandani A, Musiek F. Dichotic interaural intensity difference (DIID) training in older adults. Paper presented at: ASHA Conference; Orlando FL; 2014
71. Glyde H, Cameron S, Dillon H, Hickson L. Remediation of spatial processing deficits in hearing-impaired children and adults. J Am Acad Audiol 2014;25(6):549–561
72. Wilson RH. Development and use of auditory compact discs in auditory evaluation. J Rehabil Res Dev 1993;30(3):342–351
73. Musiek FE, Baran JA, Pinheiro ML. Duration pattern recognition in normal subjects and patients with cerebral and cochlear lesions. Audiology 1990; 29(6):304–313
74. Putter-Katz H, Adi-Bensaid L, Feldman I, Hildesheimer M. Effects of speech in noise and dichotic listening intervention programs on central auditory processing disorders. J Basic Clin Physiol Pharmacol 2008;19(3–4):301–316
75. Alonso R, Schochat E. The efficacy of formal auditory training in children with (central) auditory processing disorder: behavioral and electrophysiological evaluation. Braz J Otorhinolaryngol 2009; 75(5):726–732
76. Schochat E, Musiek FE, Alonso R, Ogata J. Effect of auditory training on the middle latency response in children with (central) auditory processing disorder. Braz J Med Biol Res 2010;43(8):777–785
77. Musiek FE, Baran JA. Audiological correlates to a rupture of a pontine arteriovenous malformation. J Am Acad Audiol 2004;15(2):161–171
78. Musiek FE, Charette L, Morse D, Baran JA. Central deafness associated with a midbrain lesion. J Am Acad Audiol 2004;15(2):133–151, quiz 172–173
79. Musiek FE, Baran JA, Shinn J. Assessment and remediation of an auditory processing disorder associated with head trauma. J Am Acad Audiol 2004;15(2):117–132