Perceptual Training of Phoneme Identification for Hearing Loss

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ABSTRACT

Synaptic connections in the auditory system change throughout life in response to the changing acoustic environment. These changes help to compensate for sensorineural hearing loss (SNHL) and the consequent impairment of high-frequency hearing by enhancing the efficiency of synaptic transmission of low-frequency signals. They also help to compensate for the inevitable deterioration in the central auditory system that occurs with normal aging even without clinically significant hearing loss. However, in many cases the neuroplastic changes are insufficient to maintain optimal speech comprehension. Indeed, the enhanced transmission of low-frequency phonetic cues that occurs with longstanding SNHL may interfere with a patient's ability to use the high-frequency phonetic cues that are restored by hearing aids. Adaptive perceptual training using tasks that require high-frequency phonetic cue processing can drive neuroplastic change in auditory cortex to improve speech discrimination. The authors tested the benefits of at-home personal computer-based phoneme identification training in new hearing aid (HA) users and found that it produced significant benefit in phoneme identification by reducing phonetic confusions and enhancing the patient's abilities to identify previously difficult syllables. Perceptual training is a promising and cost-effective tool for enhancing speech perception in HA users who have difficulty in understanding everyday speech.

KEYWORDS: Computer-based training, hearing aids, speech perception, phonemes, neuroplasticity, adaptive learning

Learning Outcomes: As a result of this activity, the participant will be able to (1) describe the neuroplastic changes that occur in phoneme perception as a result of hearing loss, and (2) explain how perceptual training can reverse these changes to improve aided speech perception.

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Auditory Training; Guest Editor, Robert W. Sweetow, Ph.D.

Semin Hear 2007;28:110–119. Published in 2007 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584–4662. DOI 10.1055/s-2007-973437. ISSN. 0734-0451.

The auditory cortex adapts to the acoustic environment throughout life.[1] This adaptation is mediated in part by synaptic flux that occurs in association with the growth and retraction of dendritic spines whose half-life is measured in months,[2] and by dendrites that change more slowly.[3] Such changes adapt the auditory cortex to its acoustic environment.[4] They underlie the specialization of the auditory cortex for processing of phonemes in the native language including optimizing the during early development.[5]

The high-frequency sensorineural hearing loss (SNHL) that often accompanies aging[6] has a profound cognitive consequences impact on communication because high-frequency speech cues are critical for consonant discrimination, especially in the presence of noise.[7] Speech understanding in noise can be measured by presenting spoken sentences at comfortable listening levels with varying degrees of concurrent masking noise. For example, the Hearing in Noise Test (HINT) presents sentences with speech-spectrum noise and adjusts the signal-to-noise ratios (SNRs) to define speech reception thresholds (SRTs) where 50% of sentences are accurately reported.[8] In young adults with normal hearing, SRTs average roughly 3.0 dB. Because accurate report of whole sentences in noise improves by 6 to 9% depending on sentence predictability,[9] young adults reach effective communication levels (i.e., 90 to 95% sentence recognition) at SNRs of + 2 to + 6 dB. Even with hearing aids, patients with SNHL require SNRs that are 8 to 10 dB higher than those of young adults with normal hearing.[10] This implies that effective communication levels for patients with SNHL would be reached at SNRs of + 10 to + 16 dB. Because the SNR of everyday speech averages + 8 dB,[11] patients with SNHL often find themselves in difficult listening conditions. The problem is not primarily inaudibility: Although hearing aids can improve SRTs in quiet by 8 to 10 dB, standard hearing aids provide only minimal benefit (1 to 2 dB) in noisy environments.[12] The use of hearing aids with directional microphones may provide greater benefit (up to 5 dB) when signal and noise are spatially separated.[13]

SNHL patients with high-frequency hearing loss show evidence of the beneficial effects of central nervous system (CNS) neuroplasticity when processing speech. In the absence of reliable high-frequency speech cues, their speech perception makes greater use of low-frequency cues such as duration of voicing[14] and the relative intensity of consonant and vowel segments.[15] Despite such neuroplastic change, speech discrimination may remain impaired because the low-frequency speech cues alone are often insufficient to understand speech, particularly in noisy listening conditions. Moreover, overreliance on the use of low-frequency phonetic cues may limit the benefit to speech processing that occurs when HAs restore high-frequency phonetic information.

Normal aging, even in the absence of hearing loss, is associated with inevitable changes in central auditory processing areas. Small white-matter lesions are found in 90% of the population by ages 65 to 75.[16] There is also significant cortical thinning,[17] and alteration in the structural properties of the cortex that occur primarily after the age of 40.[18] Within the auditory system, alterations in synaptic processing, reductions in nerve conduction velocity, alterations in inhibitory neurotransmission, and disruptions of temporal processing can be detected in central auditory pathways; and are associated with age-related declines in speech perception.[19] Older adults with clinically normal hearing display a variety of hearing impairments as well as impairments in other auditory functions.[20,21] Among the most debilitating functional deficits are impairments in speech perception in noice: Older adults without clinically significant hearing loss require SNRs that are typically 3 to 5 dB higher than those of young adults to reach comparable asymptotic levels of speech comprehension.[22]

Changes within the CNS contribute to hearing impairments in SNHL as shown in a schematic model in Fig. 1. In the young adult with normal hearing, the full complement of neural connections from the cochlea, through subcortical structures, to the auditory cortex are fully functional as shown in the top panel. The connections from auditory cortex to the auditory association areas that are responsible for phoneme identification are also intact. In the older adult with normal hearing, neural

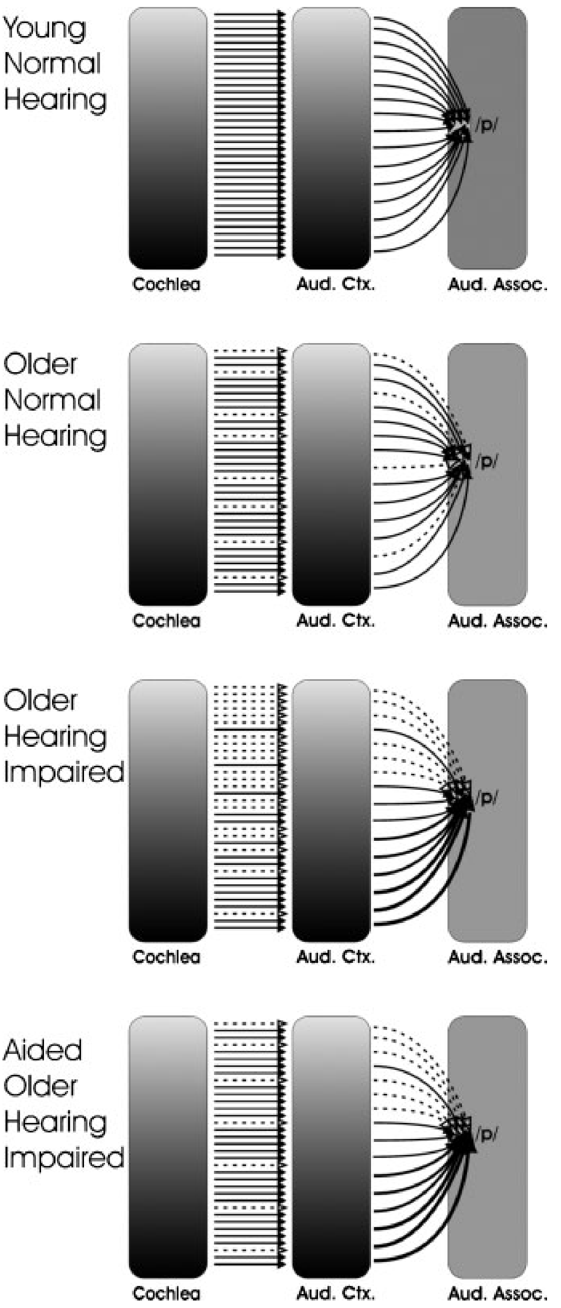

Figure 1 Information flow from the cochlea to phoneme processing regions in auditory association cortex as a function of normal aging and hearing impairment. Cochlea and auditory cortex show tonotopic organization from low to high frequency as (black to light gray). Solid lines indicate functional information flow; broken lines indicate impaired connections.

connections are lost due to random neuronal and synaptic loss that occurs with aging. Only slightly less reducing information is available for phonetic discriminations. In contrast, in the older individual with significant SNHL, there is a large reduction in high-frequency cochlear output and consequently reduced high-frequency information transmitted to the auditory cortex. Because of reduced output from high-frequency auditory cortical areas, the strength of high frequency connections to speech processing centers is reduced and the strength of low-frequency connections is correspondingly increased. Finally, when an older hearing-impaired individual is given HAs that amplify high-frequency sounds, much of the high-frequency information arriving in the auditory cortex is restored. However, the projections from auditory cortex to auditory association cortex retain their low-frequency bias due to the earlier neuroplastic changes consequent to longstanding high-frequency hearing loss. If the aided hearing-impaired individual is to optimize the use of restored high-frequency information, these neuroplastic changes must be reversed.

Unfortunately, HA use alone may be relatively ineffective. Changes in synaptic strength appear to follow the Hebbian principle that "neurons that fire together, wire together."[23] Thus, conditions needed for rewiring would primarily occur in conditions where high-frequency – but not low-frequency – phonetic cues would enable correct phonetic discrimination. Merely wearing a HA does not correct this problem because high- and low-frequency cues are highly correlated in normal listening conditions. As a result, correct discriminations would maintain connections for low-frequency cues, rather than weakening them and strengthening connections for high-frequency cues. Indeed, because the patient may actively avoid difficult listening situations where successful understanding requires the use of high-frequency cues, the conditions necessary to force high-frequency cue use may rarely occur. Moreover, even in difficult listening situations, error feedback is delayed and indirect, and hence suboptimal for driving neuroplastic change.[24]

PERCEPTUAL TRAINING WITH CONSONANT–VOWEL AND VOWEL–CONSONANT SYLLABLES

We therefore evaluated the effects of perceptual training on speech processing in patients with SNHL using a training regimen designed to force the use of high-frequency speech cues.[25] We used a syllable identification task in low-frequency speech-spectrum noise and provided immediate performance feedback after each trial.

The study participants were 50- to 80-year-old male HA users, with mild-to-moderate, symmetrical, gradually sloping, high-frequency SNHL. The immediate training (IT) group began 8 weeks of nonsense syllable identification training within one week of receiving their HAs. The delayed training (DT) group served as untrained controls for the first 8 weeks after receiving their HAs, and then began training. Participants trained in a quiet location in their homes using a multimedia personal computer (PC) equipped with calibrated loudspeakers and listened through their HAs. Each training trial included (1) the audio presentation of a syllable in noise, (2) a visual list of possible response alternatives, (3) a numerical-keypad response selection, and (4) immediate visual feedback indicating that the response was correct, or that it was incorrect along with the identity of the correct syllable. The signal-to-noise ratio (SNR) varied adaptively, decreasing by 1 dB following each correct response and increasing by 1 dB following each incorrect response. Daily training lasted 35 to 70 minutes depending on the response speed. Following each training session, the automatically connected PC to the Internet and uploaded the training data to the laboratory computer to assure training compliance. The participants trained 5 days per week for 8 weeks.

Syllable sets were selected from the City University of New York Nonsense Syllable Test (NST),[7] and mixed with speech-spectrum noise was used to mask low-frequency phonetic cues. Stimuli were consonant–vowel (CV) syllables composed of all combinations of nine unvoiced consonants (/ch/, /f/, /h/, /k/, /p/, /s/, /sh/, /t/, /th/) and three vowels (/a/, /i/, /u/), and the vowel–consonant (VC) syllables composed of all combinations of the same three vowels with nine voiced consonants (/b/, /d/, /g/, /m/, /n/, /ng/, /TH/, /v/, /z/). Two male and two female talkers recorded six examples of each of the 54 syllables. Training was done with one male and one female voice and incorporated random exemplar selection. Training and testing procedures were implemented using Presentation software, version 9.0 (Neurobehavioral Systems, Inc./Cortech Solutions, Albany, CA). Procedures and materials can be downloaded from www.neuroexpt.com.

Test sessions were conducted in the laboratory to determine the efficacy of the training. Testing in the laboratory was performed in a sound-treated test room with signals presented at 0 and 10 dB SNR using all four voices. Participants were tested unaided before they received HAs, and aided thereafter. Aided tests were done upon receipt of HAs and after 1, 2, 4 and 8 weeks of training in the immediate training (IT) group or after normal hearing aid use in the delayed training (DT) group. At that point, the DT group began training and performed laboratory test sessions after 1, 2, 4, and 8 weeks of training. Both the IT and DT groups also returned for a final test session 8 weeks after their completion of training to measure retention of the training gains. Performance feedback was not provided during testing sessions.

Fig. 2 shows the changes of NST scores relative to the initial unaided performance. There are two ordinates in Fig. 2 to clarify the magnitude of the training effects. The right ordinate shows the change in percent correct relative to unaided performance, while the left ordinate shows a conversion of percentage NST scores to dB SNR levels.[7] Mean initial (unaided) NST score averaged 34.3% over syllables delivered at 0 and + 10 dB. This score increased by 6.0% after the participants were initially fitted with HAs.

The effects of the training (solid lines) are seen in weeks 1 to 8 for the IT group and weeks 9 to 16 for the DT group. During training, highly significant gains were seen for both the IT (10.6%) and DT (8.8%) groups. There was also a small (2.4%) performance improvement in the absence of training (weeks 1 to 8 for the DT group, dashed line) that likely reflected increased familiarity with the NST procedures and possibly some acclimatization to the HAs.[26] The gains in performance due to adaptive training significantly exceeded the improvement due to hearing amplification. Moreover, although the gain for untrained voices (8.0%) was less than that for trained voices (11.5%), the improvement for untrained voices was still robust and significant. Similarly, there were

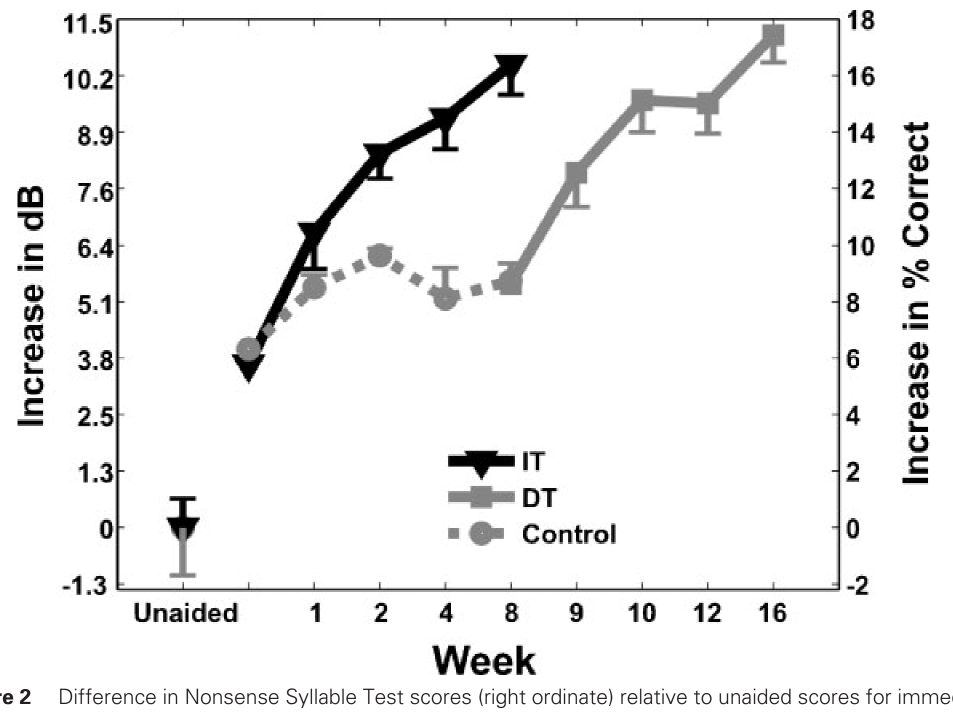

Figure 2 Difference in Nonsense Syllable Test scores (right ordinate) relative to unaided scores for immediate training (IT) and delayed training (DT) groups. The dB scale on the left is computed from percentage change in the conversion factor of 1.57%/dB from Dubno and Levitt.[7] The IT group trained for the first 8 weeks, while the DT group acted as a control group during weeks 1 through 8 and then trained from weeks 9 through 16. Standard errors are shown for each point.

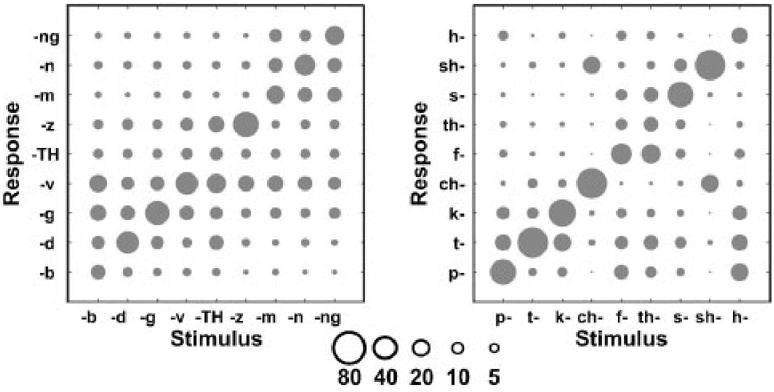

Figure 3 Stimulus/response matrices for the initial aided Nonsense Syllable Test performance. Matrices are averaged over immediate training and delayed training groups, and averaged over syllables incorporating the three different vowels used in training. Each column gives the percentage response distribution for one consonant with the area of the circle indicating the response percentage.

significant training gains at both 0 and 10 dB SNR. Finally, the IT and DT groups retained training gains, showing no significant performance decrement on retention testing at 8 weeks post-training.

Perceptual training and HA use produced a different pattern of improvement as a function of SNR: Training benefits were greater at 10 than at 0 dB SNR, whereas HA benefit showed the opposite pattern. This is consistent with the general idea that HAs provide greater benefits for speech perception at low intensity in quiet and lesser benefits at higher noise levels. Less HA benefit at the higher SNR also was expected because more speech cues would already be audible in the unaided condition. Greater training benefit for more audible stimuli is consistent with the view that perceptual training enabled HA users to make better use of speech cues that were audible at the higher SNR.

Further understanding of gains due to HA use and perceptual training can be derived from a more detailed analysis of consonant confusions. Figure 3 shows the stimulus-response matrices for the unaided condition. In these plots, perfect consonant recognition would produce large circles restricted to the diagonal; random guessing would produce uniform small circles throughout the matrix; and specific confusions would produce larger circles off the diagonal. Comparison of the two panels of Fig. 3 shows poorer performance on VCs (left) than CVs (right), as expected with the NST.[7] The pattern of responses for any particular phoneme is reflected on these graphs. For example, the CV panel on the right of Fig. 3 shows that the participants were relatively accurate for /p/, /t/, /k/, /ch/, /s/ and /sh/ identification, but initially showed poor identification of /b/, /m/, /TH/, /h/, /th/, and /f/ phonemes.

Figure 4 shows the benefits for HA amplification (top) and training (bottom) with increases represented by the areas of black circles and decreases by the areas of gray circles. Here, black circles on the diagonal and gray off the diagonal represent performance gains, while gray circles on the diagonal and black circles off the diagonal represent performance losses. Both HAs and training yielded performance gains: All of the points on the diagonals are black and most points off the diagonals are gray. Large HA benefits were found for the phonemes that were already well recognized, i.e., /p/, /t/, /k/, /ch/, /s/ and /sh/ in CVs, and /d/, /g/ and /z/ in VCs. Conversely, HAs produced little benefit for the most difficult phonemes, i.e., /f/, /th/ and /h/ in CVs, and /b/, /v/, /TH/ and /m/ in VCs.

In contrast, training produced large benefits for difficult phonemes, i.e., /f/, /th/, and /h/ for CVs, and /b/, /TH/, and /m/ for VCs. In addition, training also improved the discriminability of easier phonemes /t/ and /sh/ as reflected in the significant reduction in false identifications of both phonemes (rows 2 and 8), i.e., reductions in the likelihood of reporting /sh/

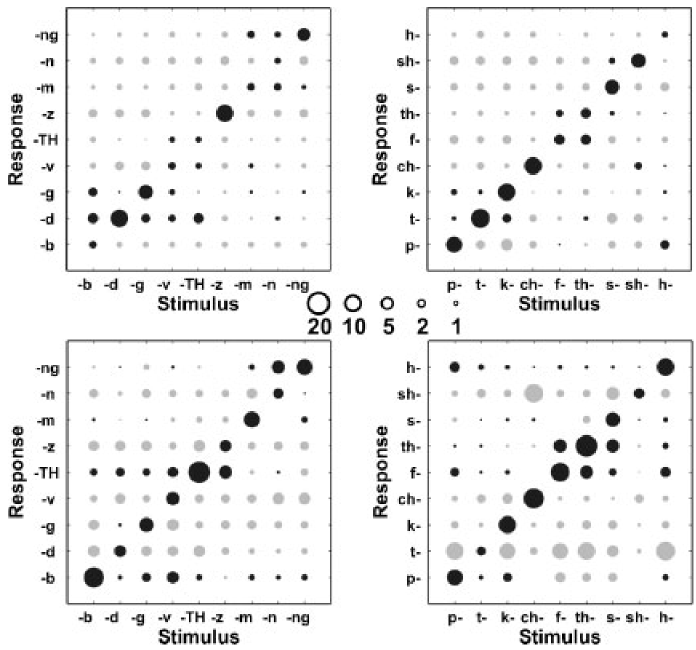

Figure 4 Changes in stimulus/response matrices due to hearing amplification (top) and due to perceptual training (bottom). Circle area shows difference in percentages for each point. Black = increase and gray = decrease. Averaged over vowels and immediate training/delayed training groups.

when /ch/ was presented and /t/ when /p/, /k/, /th/ or /h/ occurred.

These results suggest that the benefit of HAs without training was restricted to improving the audibility of currently used speech cues, whereas perceptual training extended and modified speech cue use to increase the detectability of hard to hear phonemes, and reduced phonetic confusions. In other words, perceptual training helped the participants identify and discriminate phonemes that had previously been most difficult for them, while hearing amplification provided benefit primarily for those phonemes that were already relatively easy to discriminate. These results suggest that perceptual training and hearing amplification provide complementary benefits to hearing aid users. This is consistent with the observation that training benefits were larger for adults with relatively greater initial impairments in NST scores, and tended to be larger for older than for younger adults.

Generalization of Training Benefit

A central question not addressed in the aforementioned study was the degree to which training benefits generalize to improved discrimination of conversational speech. Consider the sentence "He came in fifth." Boothroyd and Nittrouer[27] performed a careful study in which they modeled context effects on syllable, word, and sentence processing. They found that the comprehension of high-context sentences containing four consonant–vowel–consonant (CVC) words was essentially zero at SNRs where only 25% of the individual phonemes could be correctly identified in nonsense CVCs, but rose rapidly to nearly 100% at SNRs where only 80% of the phonemes could be identified in nonsense CVCs. A comparison of the results in Fig. 3 and Fig. 4 suggest that the participant's ability to identify the phonemes /h/, /m/, /f/ and /th/ were approximately doubled by training with relatively smaller improvements seen for the identification of /k/ and /n/. In the trained group, the accurate perception of the initial word "He" would provide a facilitatory context for interpreting the words "came in" that would further benefit from improved discrimination of the phonemes /k/, /m/ and /n/ due to training. Finally, the context provided by the first three words would facilitate the understanding of the final word, "fifth" that would further benefit from increases in the identification of both the /f/ and the /th/, and possibly enhance within-word context effects derived from the improved detection of the initial phonemes.[28] Phoneme identification training produced improvements in consonant identification performance that were equivalent to a 6 dB increase in SNR. If these improvements generalized to the identification of trained consonants in the test sentence, a similar improvement would be expected in SRT because the comprehension threshold (i.e., the SNR where 80% of the phonemes would be recognized in nonsense syllables) would depend on the identification threshold for the more difficult phonemes (e.g., /h/, /th/, /m/, and /f/). Thus, perceptual training might convert a sentence that is difficult for a hearing-impaired listener to understand even in a quiet living room into a message that could be perceived even in less favorable listening situations.

Because of the context-dependency of speech processing and the fact that only a portion of phonemes in a sentence can mediate understanding, hearing-impaired listeners will be relatively unimpaired when listening to common and predictable phrases, but will have difficulty processing uncommon words or phrases that are inconsistent with expectations. Thus, hearing loss can contribute to a false impression of diminished vocabulary and reduced intellectual flexibility. In addition, the hearing-impaired individual's overdependence on context would be associated with chronically increased processing effort with corresponding cognitive costs in terms of reduced verbal short-term memory and impaired retention.[29,30] Improving phoneme identification skills would be expected to improve both understanding and short-term memory, a particularly important benefit for older adults who may have additional impairments in memory function.

FUTURE DEVELOPMENT

Ultimately, the impact of perceptual training must be evaluated in conditions that mimic, as closely as possible, normal conversational listening. The most practical solution is to measure the benefits of perceptual training using comprehensive sentence testing administered before and after perceptual training.

Perceptual training entails conflicting demands: Training itself must be as focused as possible and it must maintain optimal conditions for perceptual learning with difficult discriminations performed with immediate feedback.[31,32] However, the likelihood that the benefits of syllable identification will generalize to sentence processing should be increased by the use of training sets with increased stimulus variability.[33] The isolated CVs and VCs in the study described above provided only a limited range of the consonant and vowel variability present in connected discourse. Studies are now underway to determine if more complex phonetic sequences produce greater benefit.

Another unresolved question concerns the degree to which training should be targeted to the phonetic discriminations that are likely to be most seriously impaired following SNHL. On the one hand, training focused on the identification of the most difficult phonemes would be expected to produce the largest phoneme-specific benefits. On the other hand, even modest improvements in the ability to identify easier phonemes (including vowels) might be expected to provide large increases in the ability to understand sentences because of the importance of easy phoneme discriminations in establishing sufficient context for sentence understanding in difficult listening situations. Performance might also benefit from enhancing the processing of other cues used in normal conversation. For example, training to identify speech sounds at one location when noise is present at other locations.[34] Another potential addition to auditory training is to provide coordinated visual input to improve lip reading skills using multimodal video/auditory stimulus delivery. This might prove particularly beneficial for patients with minimal residual hearing or cochlear implants.

In addition, simply increasing the duration of training might provide greater improvement. However, our previous results suggest that increasing training duration provides diminishing returns. After the first week of training, test scores increase by ~2% for each doubling of the training interval. Although benefits may develop more slowly in more complex training sequences,[35] it seems unlikely that many HA users would willingly undergo more than 2 to 4 months of training. Another path to improved training might be to start training during the critical period of "secondary plasticity" that may occur immediately after HA acquisition.[36] However, the similarity of training benefit in adults who began training immediately after receiving a hearing aid and those who began after a delay of 8 weeks, suggests that the precise time that training is started is not a major factor in limiting the magnitude of improvement. Indeed, significant training effects also were found in highly experienced HA users.[25]

Finally, although we have focused on improvements in bottom-up, phoneme identification training in this review, improvements in top-down auditory attention and memory also can play a significant role in improving speech comprehension in hearing-impaired listeners.[37,38] In the future, many different approaches to perceptual training are likely to provide significant and long-lasting benefit to the speech processing of hearing-impaired individuals.

ACKNOWLEDGMENT

Supported by NIDCD DC5814 and VA RR&D grant C2975C to DLW.

ABBREVIATIONS

CNS	central nervous system
CV	consonant vowel
CVCs	consonant–vowel–consonants
DT	delayed training
HA	hearing aid
HINT	Hearing in Noise Test
IT	immediate training
NST	Nonsense Syllable Test
PC	personal computer
SNHL	sensorineural hearing loss
SNRs	signal-to-noise ratios
VC	vowel-consonant

REFERENCES

1. Syka J. Plastic changes in the central auditory system after hearing loss, restoration of function, and during learning. Physiol Rev 2002;82(3):601–636
2. Trachtenberg JT, Chen BE, Knott GW, et al. Long-term in vivo imaging of experience-dependent synaptic plasticity in adult cortex. Nature 2002;420(6917):788–794
3. Tailby C, Wright LL, Metha AB, Calford MB. Activity-dependent maintenance and growth of dendrites in adult cortex. Proc Natl Acad Sci USA 2005;102(12):4631–4636
4. Wang X. The unexpected consequences of a noisy environment. Trends Neurosci 2004;27(7):364–366
5. Kuhl PK. Early language acquisition: cracking the speech code. Nat Rev Neurosci 2004;5(11):831–843
6. Chisolm TH, Willott JF, Lister JJ. The aging auditory system: anatomic and physiologic changes and implications for rehabilitation. Int J Audiol 2003;42(Suppl 2):2S3–10
7. Dubno JR, Levitt H. Predicting consonant confusions from acoustic analysis. J Acoust Soc Am 1981;69(1):249–261
8. Nilsson M, Soli SD, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. J Acoust Soc Am 1994;95(2):1085–1099
9. Boothroyd A. Perception of speech pattern contrasts from auditory presentation of voice fundamental frequency. Ear Hear 1988;9(6):313–321
10. Kuk F, Keenan D, Lau CC, Dinulescu N, Cortez R, Keogh P. Real-world performance of a reverse-horn vent. J Am Acad Audiol 2005;16(9):653–661
11. Pearsons KS, Bennett RL, Fidell S. Speech levels in various noise environments. In: EPA, ed. EPA-600/1-77-025. Vol 600. Washington, DC: Office of Health and Ecological Effects; 1977
12. Saunders GH, Cienkowski KM. Acclimatization to hearing aids. Ear Hear 1997;18(2):129–139
13. Ricketts T, Henry P, Gnewikow D. Full time directional versus user selectable microphone modes in hearing aids. Ear Hear 2003;24(5):424–439
14. Revoile SG, Holden-Pitt L, Pickett JM. Perceptual cues to the voiced-voiceless distinction of final fricatives for listeners with impaired or with normal hearing. J Acoust Soc Am 1985;77(3):1263–1265
15. Hedrick MS, Younger MS. Labeling of /s/ and [see text] by listeners with normal and impaired hearing, revisited. J Speech Lang Hear Res 2003;46(3):636–648
16. Launer LJ, Berger K, Breteler MM, et al. Regional variability in the prevalence of cerebral white matter

lesions: an MRI study in 9 European countries (CASCADE). Neuroepidemiology 2006;26(1):23–29
17. Salat DH, Buckner RL, Snyder AZ, et al. Thinning of the cerebral cortex in aging. Cereb Cortex 2004;14(7):721–730
18. Ge Y, Grossman RI, Babb JS, Rabin ML, Mannon LJ, Kolson DL. Age-related total gray matter and white matter changes in normal adult brain. Part II: quantitative magnetization transfer ratio histogram analysis. Am J Neuroradiol 2002;23(8):1334–1341
19. Frisina RD, Walton JP. Age-related structural and functional changes in the cochlear nucleus. Hear Res 2006:216–217216–223
20. Willott JF, Hnath Chisolm T, Lister JJ. Modulation of presbycusis: current status and future directions. Audiol Neurootol 2001;6(5):231–249
21. Divenyi PL, Stark PB, Haupt KM. Decline of speech understanding and auditory thresholds in the elderly. J Acoust Soc Am 2005;118(2):1089–1100
22. Schneider BA, Daneman M, Murphy DR. Speech comprehension difficulties in older adults: cognitive slowing or age-related changes in hearing? Psychol Aging 2005;20(2):261–271
23. Edeline JM. Learning-induced physiological plasticity in the thalamo-cortical sensory systems: a critical evaluation of receptive field plasticity, map changes and their potential mechanisms. Prog Neurobiol 1999;57:165–224
24. Robertson IH, Murre JM. Rehabilitation of brain damage: brain plasticity and principles of guided recovery. Psychol Bull 1999;125(5):544–575
25. Stecker GC, Bowman GA, Yund EW, Herron TJ, Roup CM, Woods DL. Perceptual training improves syllable identification in new and experienced hearing-aid users. J Rehabil Res Dev 2006; 43:537–552
26. Yund EW, Roup CM, Simon HJ, Bowman GA. Acclimatization in wide dynamic range multichannel compression and linear hearing aids. J Rehabil Res Dev 2006;43:517–535
27. Boothroyd A, Nittrouer S. Mathematical treatment of context effects in phoneme and word recognition. J Acoust Soc Am 1988;84(1):101–114
28. Benki JR. Quantitative evaluation of lexical status, word frequency, and neighborhood density as context effects in spoken word recognition. J Acoust Soc Am 2003;113(3):1689–1705
29. McCoy SL, Tun PA, Cox LC, Colangelo M, Stewart RA, Wingfield A. Hearing loss and perceptual effort: downstream effects on older adults' memory for speech. Q J Exp Psychol A 2005;58(1):22–33
30. Wingfield A, Tun PA, McCoy SL. Hearing loss in older adulthood: What it is and how it interacts with cognitive performance. Curr Dir Psych Sci 2005;14:144–148
31. Ahissar M. Perceptual training: a tool for both modifying the brain and exploring it. Proc Natl Acad Sci USA 2001;98(21):11842–11843
32. Goldstone RL. Perceptual learning. Annu Rev Psychol 1998;49:585–612
33. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. Curr Opin Neurol 2006;19(1):84–90
34. Murphy DR, Daneman M, Schneider BA. Why do older adults have difficulty following conversations? Psychol Aging 2006;21(1):49–61
35. Watson CS. Time course of auditory perceptual learning. Ann Otol Rhinol Laryngol Suppl 1980; 89(5 Pt 2):96–102
36. Willott JF. Physiological plasticity in the auditory system and its possible relevance to hearing aid use, deprivation effects, and acclimatization. Ear Hear 1996;17(3 Suppl):66S–77S
37. Sweetow RW, Henderson Sabes J. The need for and development of an adaptive listening and communication enhancement (LACE) program. J Am Acad Audiol 2006;17:538–558
38. Sweetow R, Palmer CV. Efficacy of individual auditory training in adults: a systematic review of the evidence. J Am Acad Audiol 2005;16(7):494–504