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Effects of Training on Recognition of Musical Instruments Presented through Cochlear Implant Simulations

Virginia D. Driscoll^{*}, Jacob Oleson[†], Dingfeng Jiang[†], and Kate Gfeller^{‡,§}

^{*}Iowa Cochlear Implant Clinical Research Center, University of Iowa Hospital and Clinics

[†]Department of Biostatistics, University of Iowa College of Public Health

[‡]School of Music, University of Iowa

[§]Department of Speech Pathology and Audiology, Iowa Cochlear Implant Clinical Research Center, University of Iowa

Abstract

Background—The simulation of the CI (cochlear implant) signal presents a degraded representation of each musical instrument, which makes recognition difficult.

Purpose—To examine the efficiency and effectiveness of three types of training on recognition of musical instruments as presented through simulations of the sounds transmitted through a CI.

Research Design—Participants were randomly assigned to one of three training conditions: repeated exposure, feedback, and direct instruction.

Study Sample—Sixty-six adults with normal hearing.

Intervention—Each participant completed three training sessions per week, over a five-week time period, in which they listened to the CI simulations of eight different musical instruments.

Data Collection and Analysis—Analyses on percent of instruments identified correctly showed statistically significant differences between recognition accuracy of the three training conditions ($p < .01$).

Results—those assigned to the direct instruction group showed the greatest improvement over the five-week training period as well as sustained improvement after training. The feedback group achieved the next highest level of recognition accuracy. The repeated exposure group showed modest improvement during the first three-week time period, but no subsequent improvements.

Conclusions—These results indicate that different types of training are differentially effective with regard to improving recognition of musical instruments presented through a degraded signal, which has practical implications for the auditory rehabilitation of persons who use cochlear implants.

Keywords

Auditory rehabilitation; cochlear implant; music; normal hearing; simulations; training

Cochlear implants (CI) are assistive hearing devices that provide significant benefit in perception of speech for individuals with pre- and postlingual deafness. Longitudinal studies

Virginia D. Driscoll, University of Iowa, Department of Otolaryngology, 21033 PFP, 200 Hawkins Dr., Iowa City, IA 52242-1078; Phone: 319-356-3908; Fax: 319-384-6744; E-mail: virginia-driscoll@uiowa.edu.

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reveal that most recipients of CIs can achieve significant improvement in speech perception within three months after implantation as a result of everyday use; some CI users reach maximum benefit after 36 months postimplantation (Tyler et al, 1997; Ruffin et al, 2007). This typical pattern of improved speech reception is possible in part because the implant is well-suited for transmitting the most salient features of speech, especially in quiet. Furthermore, CI recipients have ready access to a number of visual cues (e.g., speech reading, closed captioning) that can support the development of speech reception in everyday life.

Unfortunately, current limitations in implant technology result in less effective transmission of salient features needed for accurate music perception and enjoyment. In particular, recipients of CIs are significantly less accurate than listeners with normal hearing in music perception tasks such as pitch perception (Gfeller et al, 2005, 2007; Gfeller, Turner, et al, 2002; Kong et al, 2004; McDermott, 2004), melody recognition (Gfeller et al, 2005, 2007; Gfeller, Turner, et al, 2002; Kong et al, 2004; McDermott, 2004; Olszewski et al, 2005), and recognition of musical instruments (timbre recognition) (Dorman et al, 1991; Gfeller and Lansing, 1991; Gfeller et al, 1997, 1998; Gfeller, Witt, Adamek, et al, 2002; Gfeller, Witt, Woodworth, et al, 2002; McDermott and McKay, 1997; Pijl, 1997; Fujita and Ito, 1999; Leal et al, 2003; Schon et al, 2004; Pressnitzer et al, 2005; Laneau et al, 2006). There are melodies, however, a few individuals, commonly referred to as “star users,” are able to recognize using pitch perception. Furthermore, while CI recipients demonstrate significantly improved speech reception as a result of everyday experience over time, most CI recipients do not enjoy the same level of improvement for music perception and enjoyment as a result of incidental exposure over time (Gfeller et al, 2001, 2008). Some type of direct effort or rehabilitation is required for many CI recipients to improve music perception.

Auditory Rehabilitation

The primary objective of auditory rehabilitation for persons with hearing loss is to promote optimal use of residual hearing. This includes maximizing listener benefit from the less than perfect acoustic signals transmitted by a hearing aid or cochlear implant. Auditory rehabilitation has been found effective in improving perception of speech or music for individuals with CIs (Gfeller et al, 1998, 1999, 2001; Gfeller, Witt, et al, 2000; Wei et al, 2000; Neuman, 2005), though the extent of improvement varies depending upon a number of factors. Among those factors believed to influence improvement are cortical plasticity (including age-related changes), complexity of the task, similarity between training and testing tasks, life experiences, and individual differences.

Cortical plasticity, which is defined as change that occurs in information processing functions of the brain (Buonomano and Merzenich, 1998), is an important factor in auditory rehabilitation in adults. Specifically, the cortex reorganizes local neural connections and responses as a result of input (e.g., the types of sounds heard in everyday life) and behavior (e.g., having or seeking opportunities to hear many types of sounds) (Buonomano and Merzenich, 1998).

Cortical plasticity varies as a result of many factors including age. Age can affect multiple levels of performance, including auditory temporal processing, increasing presbycusis, and increased interaural asymmetry, which is a result of declines in interhemispheric transfer of auditory information and central processing (Martin and Jerger, 2005). Gordon-Salant and Fitzgibbons (1995) compared the ability of two groups (one younger than 40 and one older than 65) to process a degraded stimulus. Each age group included participants with normal hearing or mild-to-moderate hearing losses. Results showed that younger listeners, both with and without hearing loss, were able to process a degraded stimulus more accurately than the older listeners with comparable hearing. Age effects were found to be significant for listeners with normal hearing and those with hearing losses. More specifically, participants in the 65–

75 year age range were less accurate in conditions featuring time compression. The authors speculated that results were due to the global slowing of processing associated with the aging process, and that age affects speech recognition tasks that utilize multiple forms of degraded stimuli (Gordon-Salant and Fitzgibbons, 1995). Older listeners had a reduced functional signal-to-noise ratio in listening conditions that consisted of multiple degradations of speech signals (Gordon-Salant and Fitzgibbons, 1995).

In addition to cortical plasticity and age, the listening task also influences the effectiveness of auditory rehabilitation. With regard to the complexity of the task (e.g., greater complexity associated with multiple talkers, unfamiliar speech patterns, or complex music), the greater the complexity, the longer the learning period required to achieve significant benefit (Robinson and Summerfield, 1996). As the set size of a task increases, the demands on memory and attention also increase resulting in greater levels of difficulty (Gordon-Salant and Fitzgibbons, 1995; Robinson and Summerfield, 1996; Burkholder et al, 2005; Pressnitzer et al, 2005). In addition, the more similar the listening task is to prior listening experiences, the easier the rehabilitation. Because the sound of music is altered significantly through a CI, and because music is often comprised of complex combinations of many voices or instruments, there is likely to be a relatively large amount of information to be perceived, organized, and identified by a CI user in auditory rehabilitation of musical sounds (Robinson and Summerfield, 1996). Additionally, the greater the similarity between training and testing conditions (i.e., format, layout, interaction, etc.), the more the user is able to apply the learned information in the testing session (Robinson and Summerfield, 1996).

Trainee factors (e.g., life experiences, cognitive skills) also can affect the rate of learning in auditory rehabilitation. For example, life experiences in music listening and the knowledge of musical instruments prior to and throughout training can influence rehabilitative benefit. Cognitive attributes such as attention and memory, as well as measures of cognitive flexibility, which interact with the complexity of the cognitive task, also influence auditory rehabilitation. The importance of cognitive processing is illustrated by prior studies of CI recipients (Gfeller et al, 2001, 2008), which indicate that CI users with greater sequential processing capabilities, typically associated with attentional memory, show greater accuracy on music perception, including timbre recognition.

Specific to training of music instrument recognition, a handful of studies indicate that timbre perception of CI users can improve as a result of feedback or other forms of training (e.g., Gfeller et al, 1999, 2001; Gfeller, Witt, et al, 2000; Gfeller, Witt, Adamek, et al, 2002; Leal et al, 2003; Pressnitzer et al, 2005). In a study of timbre recognition (Leal et al, 2003), 29 adults with CIs were tested on accuracy to recognize an instrument when given a choice between three instruments from distinct musical families (i.e., string, brass, and pitched percussion). Analyses revealed that 68% were able to accurately recognize all three instruments. While the scores obtained in this study were higher than those reported in comparable studies (e.g., Gfeller and Lansing, 1991; Gfeller et al, 1998; Gfeller, Turner, et al, 2002; Gfeller, Witt, Adamek, et al, 2002; Gfeller, Witt, Woodworth, et al, 2002), the authors acknowledged the small closed-set of possible choices and hypothesized that a larger number of choices would have resulted in poorer results. It is unclear whether these results could extend to a larger sample with more choices.

Pressnitzer et al (2005) examined the influence of attack time and spectral center of gravity on timbre recognition, incorporating adaptive procedures with some initial training and feedback in an alternate forced-choice. After feedback received during the training period, CI recipients enrolled in the study showed a “good level of performance” on timbre discrimination. The authors concluded that the ability of CI recipients to discriminate changes in attack time and spectral center of gravity should allow for musical instrument recognition after some training.

Gfeller et al (1999, 2000); Gfeller, Witt, et al (2000); and Gfeller, Witt, Adamek, et al (2002) compared musical instrument recognition for CI recipients enrolled in a 12-week, home-based computer training program with CI users who had only incidental experience (control group) to music during that same time period. Results revealed that the training group showed significant improvement ($p < .01$) in instrument recognition following 12 weeks of training, while those in the control group did not.

In summary, a number of studies have identified factors that influence benefit of auditory rehabilitation for speech perception. Furthermore, prior studies indicate that musical instrument recognition can improve as a result of training (Abdi et al, 2001; Gfeller, Witt, Adamek, et al, 2002; Gfeller, Witt, Woodworth, et al, 2002; Pressnitzer et al, 2005). It is not yet known, however, what sorts of training (e.g., type of training) are most effective, or how much training is sufficient in order for CI recipients to achieve significant improvement in specific music listening tasks. Further research is needed to determine those components of training that result in the most efficient and effective improvement for specific aspects of music perception.

One of the difficulties in assessing the efficacy of different training approaches with CI recipients is the potentially confounding variables among recipients of CIs with regard to the primary hearing mechanisms. Individuals with cochlear implants vary on physiological factors such as electrode-nerve interface, nerve survival, number of implanted electrodes, and amount of current spreading from stimulating electrodes, which can affect the amount of benefit they receive from their devices (Fu and Nogaki, 2004; Nie et al, 2006). This makes it difficult to recruit a relatively homogeneous sample of CI recipients with regard to potentially confounding factors (such as length of deafness, or varying patterns of nerve survival). One possible methodological alternative to testing the CI recipient is the use of cochlear implant simulations with individuals who have normal hearing.

Studies Using Simulations with Adults with Normal Hearing

A number of researchers have used engineered simulations of the CI signal in order to test those aspects of the signal most salient to perceptual accuracy and sound quality, both for speech (Gordon-Salant and Fitzgibbons, 1995; Shannon et al, 1995; Lakshminarayanan et al, 2003; Qin and Oxenham, 2003; Fu, Nogaki, et al, 2005; Fu and Nogaki, 2004; Poissant et al, 2006; Nogaki et al, 2007) and for music (Moore and Tan, 2003; Burkholder et al, 2005; Limb, 2006). Previous investigations produced comparable results between simulations and actual cochlear implant listening (Shannon et al, 1995; Lakshminarayanan et al, 2003; Moore and Tan, 2003; Qin and Oxenham, 2003; Fu and Nogaki, 2004; Burkholder et al, 2005; Fu, Nogaki, et al, 2005; Poissant et al, 2006). Additionally, researchers have emphasized the benefit of greater numbers of participants with normal hearing who are available, as well as the more precise control of the processing characteristics and parameters to be manipulated when simulations are used (Poissant et al, 2006). These benefits were perceived as relevant to the research at hand, and consequently, cochlear implant simulations were used in this study, presented to participants with normal hearing.

The purpose of this study was to compare the efficacy of three approaches to training: repetition, feedback, and direct instruction on the ability of a listener to acclimatize to a distorted signal and to recognize simulations of the signal of musical instruments as transmitted through a CI. Repeated exposure (RE) closely resembled real-life situations (e.g., turning on the radio and listening to music) in which no feedback on the sound source is available. Feedback training (FB) evaluated the effectiveness of trial and error, where answers that are recognized as correct are more likely to be repeated. Direct instruction (DI) evaluated an educational situation in which one is presented with directed information about the stimuli and

encouraged to remember it across future presentations, as it is introduced and tested and as feedback regarding accuracy also is provided.

It was predicted that the participants who received the direct instruction (DI) would improve significantly in correct identification of instruments, individuals who received feedback (FB) would improve marginally, and participants exposed repeatedly to stimuli (RE) would maintain scores of chance, as has been reported in prior studies of CI recipients' perceptual accuracy for musical instruments (Gfeller et al, 1998; Gfeller, Witt, Adamek, et al, 2002). In the present experiment, because the training programs required identification, which is more difficult than mere discrimination, it was predicted that a longer period of training would be necessary than has been required in studies utilizing discrimination only tasks, as were used in acute laboratory testing experiments (e.g., Robinson and Summerfield, 1996; Pressnitzer, 2005). While Gfeller, Witt, Adamek, et al (2002) provided training consisting of 48 lessons over a 12-week time period, that study did not measure change over time, thus, it was not evident how much time and exposure was essential to achieve significant improvement. Consequently, the study at hand included multiple measures over the entire training period in order to examine the time factor as well as magnitude of change from pre- to posttest associated with the three contrasting training approaches.

Method

Participants

Listeners with normal hearing were selected in this study in order to eliminate factors such as the health of the peripheral auditory system or variables associated with implantation (e.g., number of channels activated, placement of the array within the cochlea, etc.) and to more clearly determine improvement as a result of the training provided. Participants were recruited through newspaper advertisements. Normal hearing was defined as pure-tone thresholds of ≤ 20 dB HL tested at the following frequencies: 250, 500, 1000, 2000, and 4000 Hz. Those individuals who were unable to meet the hearing criteria were excused from research ($n = 10$). Participants included 66 listeners with normal hearing (14 males, 52 females) who ranged in age from 18 to 69 years ($M = 37.52$, $SD = 12.81$). Because age is considered an important factor in cognitive functioning and in benefit from auditory rehabilitation, our recruitment criteria included normal-hearing participants between ages 18 and 75. These criteria reflect the age range of adult CI recipients in our center. We used a stratified sampling in order to have equal representation of men and women for each six-year age range within that continuum. Each participant was required to have a home computer with Internet access and sound capabilities. Participants received compensation for participating in the study. The human subject protocol was approved by the institutional review board.

Stimuli

CI simulations were prepared from recordings of eight different musical instruments that are commonly known in the United States, and for which extant research data with CI recipients are available, both for timbre recognition and for effects of training on recognition (Gfeller et al, 1998; Gfeller, Witt, Adamek, et al, 2002; Gfeller, Witt, Woodworth, et al, 2002; McDermott, 2004). These instruments represented different principles of sound production (e.g., reed-flute, lip buzzing, etc.) and a continuum of frequency ranges from high to low. The instruments included the flute, clarinet, saxophone, trumpet, trombone, violin, cello, and piano. Each instrument was recorded playing the same three simple melodic patterns developed for research purposes. These melodies included a seven-note melody adopted from prior studies conducted by Gfeller et al (1998); Gfeller, Witt, Adamek, et al (2002); and Gfeller, Witt, Woodworth, et al (2002) and two standardized melodic phrases of 14 and 15 notes each composed by the researcher that included an octave range with interval changes between one and seven

semitones. In addition to these standardized melodic phrases, a 6–12 sec excerpt from one composition considered typical of the repertoire for each instrument was recorded. The selection of a composition considered “typical” for each instrument was determined by seeking the input of university instructors who are specialists on each instrument and who were asked to choose a “real-world” selection that would be considered a classic example of repertoire for that instrument, and that shows off the most stereotypical frequency range and sound characteristics of that instrument (e.g., “Trumpet Voluntary” by Purcell for the trumpet).

The woodwind, brass, and string instrumental excerpts were performed by professional musicians who were recorded using a single AT 4041 microphone. Because the piano could not be moved into the recording studio, a SONY portable minidisc walkman digital recording device MZ-R55 and SONY Electret Condenser Microphone ECM-MS907 were used, and the recordings were then transferred to the location of the other audio files. The input/output (I/O) device used to record onto the computer hard drive was a Digidesign Digi 002 Rack (a firewire based audio I/O). Pro Tools LE 6.9 software was used to record and edit the examples. After the editing was completed, the files were converted to a useable format to create an individual mono audio interchange file format (AIFF) file for each melody played by each instrument. These recordings were then modified into CI simulations.

CI Simulations—A six-channel simulation of the signal transmitted by a CI was created by using a six-channel vocoder implemented using Matlab (Rubinstein and Turner, 2003; Drennan et al, 2007). Original signals were band pass filtered into six frequency bands with cutoff frequencies shown in Table 1.

The envelope of the original signal was extracted from each band using the magnitude of the Hilbert transform. The Hilbert phase was then randomized and bandpass filtered to band-limit the randomized fine-structure to the same sub-band. The randomized fine-structure was then modulated by the Hilbert envelope and the sub-bands summed to produce the final output, which is equivalent to a vocoded signal using band-limited noise bands (Rubinstein, 2004). After all of the recorded melody patterns and excerpts (which as a group will be referred to as the instrumental simulations) were modified, they were normalized to equal RMS (root mean square) amplitude. All the instrumental simulations were then integrated into a training program that was delivered via a Web-based computerized training program. Qualitative reports from the participants described the cello as sounding like “waves”; the piano (and its percussive onset) was likened to construction.

Training Program Lessons

The training program consisted of 15 lessons, completed over a five-week time period (three lessons per week). The lessons were delivered via a Web site to be accessed by computer using an Internet connection in the participants' homes. Lessons were password-protected to prevent crossover from a different training condition. For individuals with slow Internet access (e.g., dial-up), or who were missing needed software components, universal serial bus (USB) drives containing the training program lessons were provided. Participants were asked to complete the lessons three times per week for five weeks and were encouraged to complete only one lesson per day; each lesson lasted approximately 12 minutes. Programs were created using Microsoft Visual Basic 6.0 and uploaded to the Internet as encrypted file transfer protocol (ftp) files. Sound files used in the programs were object linked and embedded (OLE) audio files to allow for ease of transmission. In each lesson, each instrument was represented with one melodic pattern that was presented four times per lesson. Over the five-week period, each instrument was presented a total of 60 times. Each instrumental melody was presented in four lessons over the entire training period.

Experimental Conditions

The 66 participants were randomly assigned to one of three experimental conditions ($n = 22$ per group), as a stratified sample based on age and gender (1) RE-repeated exposure, (2) FB-exposure plus feedback, and (3) DI-exposure with directed instruction. Each treatment condition included the same instrumental simulations and the same number of exposures to each item.

The first condition, RE, consisted of repeated exposure to the simulations. In this training condition, participants were asked to listen to the simulations of the eight instruments. After listening to each instrumental item, the participant was asked to indicate which instrument they had just heard by clicking on one of 12 instrument icons presented via computer screen as a visual guide (bells, harp, guitar, drums, piano, flute, saxophone, clarinet, violin, cello, trombone, and trumpet). The RE group received no direct information about which instruments they were listening to, and no feedback regarding the accuracy of their instrument identification. The repeated exposure to musical instruments without information or feedback resembles to some extent the “real-world” listening task of hearing an instrument on a recording or on the radio, and having no supporting visual information (e.g., not being able to watch the performer play the instrument) or label (such as having the radio announcer state that you just listened to a trumpet, piano, or other instrument) to help identify the source of the sound. An improvement in this condition would reflect acclimatization to the signal in response to mere exposure.

The FB condition, like the RE condition, provided repeated exposure to the instrumental simulations. In addition, after the participants selected which instrument they thought they had heard via the computer interface, they received feedback on the computer screen about whether their selection was correct or incorrect. No additional information regarding which instrument had actually been played was given. Thus, they received some limited feedback on their accuracy but no direct instruction regarding the sound of each instrument.

The DI condition also provided repeated exposure to the instrumental simulations. However, the participant was given direct information during only the initial presentation of the simulation via the computer about which instrument they were hearing, and were instructed to listen for specific characteristics of the instrument and the timbral components that might be heard in each audio excerpt (e.g., “The sound of the flute is thin and airy”; “The trumpet has a crisp start to the notes and each is well-focused”). Information regarding the typical use, history, and mechanics of the instruments were provided to aid in the learning and recognition. After the first presentation of each instrument, which included direct instruction in each lesson, the remaining three exposures were identical in format to the FB condition and the participants received “correct” or “incorrect” in response to their selections. In all three conditions, the participants completed three lessons per week over a five week period, with simulations of each instrument presented four times per lesson.

Measurement

Pre-training Measures—Data collection included the following measures: (1) a questionnaire, which provided a score of the person's prior musical training and listening experiences, (2) a computerized test of paired associate memory, and (3) the instrumental recognition test to determine baseline accuracy on recognition of the instrumental simulations. These measures are described below.

Music Background Questionnaire (MBQ)—Because some studies indicate that musical experiences can influence perceptual accuracy of CI recipients (Gfeller et al, 2006, 2008), a questionnaire was administered to determine the participants' musical background and

experience, as well as a self-report of musical instruments that they believed they could recognize by sound alone. Musical background and experience was based on experience with musical instruction/participation in primary, secondary, and tertiary education and ensembles as well as participation in community ensembles following the completion of their education. The score derived from this questionnaire, based on the scoring system used by Gfeller, Christ, et al (2000) was included in the analyses of the results as a possible influential factor in outcome.

Paired Associate Memory Test (PAT)—The training program essentially requires the participant to associate the degraded signal of the simulation with given musical stimulus. In order to do this, the participant would have to “pair” the sound they heard with the corresponding instrument. While the PAT measure is not dependent on verbal skill or aural presentation, the test is similar in style to that of the training protocol. Because individual differences in paired associate memory could potentially influence the extent of benefit from training, prior to the commencement of the training period, each participant completed a paired associate memory test (PAT) to account for this individual difference (Knutson, 2006). This test requires the participant to learn pairings of numbers (1-9) with twelve two-dimensional geometric forms (three numbers are paired with two geometric forms; six are paired with one geometric form each). In this test, participants were asked to learn the number that the computer corresponded with each geometric form. The participant was shown a geometric form on a computer screen and asked to guess which number, between and including 1 and 9, the computer paired to that geometric form. Immediately following the participant's response, feedback (correct/incorrect) was provided regarding the number that corresponded to that geometric form, and the participant was given 8 sec to view the figure with the correct number before the next figure was presented. Once the computer paired a number to a geometric shape, that number/geometric shape relationship did not change throughout the test. The entire series of pairings was repeated ten times for a total of 120 presentations. Scores for this test were calculated by total percentage correct for each of the ten series.

Instrumental Simulation Recognition Test—The instrumental recognition test administered consisted of a 12-alternative forced-choice (12AFC) test and was scored in total number correct and percent correct. Test stimuli were presented at 65 dBC in free field in a sound-treated room. Participants were allowed to adjust the volume to accommodate their level of comfort after the initial setting was made. The computer interface consisted of pictures (photograph or realistic drawing) of each instrumental choice, as well as the corresponding name written out when the mouse was positioned over the picture. During testing, participants were asked to click the mouse on the picture of the instrument they believe had been presented after each simulated melody was played. Five different melodies were presented for each instrument one time, for a total of 45 presentations. No participants received any form of feedback during the testing conditions. The same test was administered (instrumental simulation recognition) for participants in all conditions at the following subsequent time intervals: midpoint (week 3), posttraining (week 5), and in follow-up testing (week 7). Weeks 3 and 5 were measured in order to track the trajectory (rate) of improvement over the five-week training period; week 7 was tested to determine retention of learning without additional instruction.

Upon completion of the music background questionnaire, PAT, and pretest for instrumental recognition, participants were randomly assigned to their experimental condition. Web site address, instructions on lessons, and a password to access lessons were provided to participants, and the first of two follow-up visits were scheduled.

Midpoint Measurement

Participants returned to our center for midpoint testing in the third week of the training program for instrument simulation recognition testing only. This measure was used to help determine rate as well as magnitude of change over time.

Posttraining Measurement

After completion of the five-week training program, all participants returned to the center for posttesting with the instrumental simulation recognition test to determine the extent of improved recognition immediately following training. Participants returned one more time for follow-up testing in week 7 to evaluate the amount of learning retained in the absence of training. After the final evaluation in week 7, each participant was then tested on their recognition of the original instrumental recordings (not simulations) of each instrument in order to confirm the participant's self-report regarding prior familiarity with the musical instruments in the test. Test content, protocol, and timing (Week 1, 3, 5, and 7) was identical for each condition and was administered on the same computer each time.

Data Collection

Data collected during the pre-, the mid-, and the two posttesting visits were recorded into a text file on the testing computer. Correct and incorrect responses and testing percentages of correct responses were recorded and tracked to evaluate change over time. All test results were entered into databases for analyses using assigned identification numbers in order to protect the confidentiality of each participant.

Results

Variables included in the analyses were training conditions, time (four points of measurement), musical instruments known prior to testing, age of participant, musical background (as measured by the questionnaire), and associative memory (PAT). The dependent variable in this study was percentage of musical instruments correctly identified in the instrumental simulation recognition test. This outcome variable was treated as binomial (number correct out of five melodies). The outcome measure for each individual was recorded at four points in time (week 1, week 3, week 5, and week 7) on each of the musical instruments. There were 45 observations per participant per test time giving a total of 180 observations by the follow-up visit (week 7).

A generalized linear mixed model (GLMM) was developed for the analysis. An analysis comparing more than two groups is typically performed using ANOVA (analysis of variance) when the response variable is continuous. In this experiment, an ANOVA was deemed unsuitable. The outcome variable resulted in the number of correct answers out of five trials, thus not satisfying the normality assumption in ANOVA. Because the response variable was binomial rather than continuous, we used a logit transformation on the percent correct (i.e., $\log[p/(1-p)]$). In addition to testing the differences between these three conditions, it was hypothesized that musical instrument identification also was related to time (weeks 1, 3, 5, and 7) plus additional covariates. Time likely interacted with condition (RE, FB, DI) as well; that is, the three experimental conditions may have performed differently at each of the four points in time. Another aspect of this model was that participant was treated as a random effect to account for within subject variability because the same participant was measured at multiple times. Musical instrument also was treated as a random variable to account for variability within an instrument. Where there are both fixed and random effects, the model is known as a mixed model. The GLMM analyses were performed using SAS Version 9.1 Proc GLIMMIX (SAS Institute, Inc., 2004).

The predictor variables in the model were experimental condition membership (RE, FB, DI), time of testing (weeks 1, 3, 5, and 7), within the training process, gender, age, number of instruments known prior to testing, past music experience (MBQ), and PAT, as well as interactions between condition by age and condition by time of testing (weeks 1, 3, 5, or 7). Interactions were included because the difference between the conditions varied based on time and potentially by age. For example, Figure 1 shows evidence of a condition by time interaction. The height of the bars represents the average percent of instruments identified correctly for the group. The corresponding error bars display one standard error. For the RE condition, time has very little impact on probability of correct response because we see the height of the bars are relatively unchanged over time. However, for the FB and DI conditions we see the probability of correct response increasing from week 1 to week 3 and week 3 to week 5. That probability then maintains from week 5 to week 7. If these three conditions all showed the same pattern, then interaction would not be needed in the model. When the patterns differ between the conditions, then an interaction term is necessary.

Musical instrument was treated as a random effect with a variance components error structure. The variance components structure allows each instrument to have its own variance rather than one constant variance for all instruments. There also was a random intercept for each participant. This allows for within-subject correlation which is modeled with the Toeplitz error structure. The Toeplitz error structure specifies decreasing correlation over time where a distance of one point in time apart has a correlation equal to ρ_1 , a distance of two points in time apart has a correlation equal to ρ_2 , and a distance of three points in time apart has a correlation equal to ρ_3 .

Results for Four Testing Times

Of the nine predictor variables (two of which are interaction terms), four were significant at the level of 0.05: experimental condition, time when tested (week), music experience, and interaction of condition and week (Table 2).

From parameter estimates, we found that prior music experience (as measured by the MBQ) had a positive relationship with the percentage of correct answers ($p < .01$). Age of participant was not significant at the level of 0.05 ($p = .35$). We note, though, that the parameter estimate was negative (-0.01), which could indicate a tendency for older participants to perform more poorly than younger participants in recognition of musical instrument simulations.

From Table 2 we see that there is significant interaction of condition by week ($p < .01$). When interaction is present, the main effects should not be evaluated on their own since the main effects do not take into account the fact that the impact of week will differ depending on condition and vice versa. The effects for week in each condition are presented in Table 3 (the effects of condition for each week are presented in Table 4). The results for the RE condition indicated a significant improvement from week 1 when compared to weeks 3, 5, and 7, but no significant improvements from week 3 to week 5 or 7. For FB and DI conditions, both conditions resulted in a significant improvement in weeks 3, 5, and 7 compared with the score in week 1. The participants demonstrated a significantly better performance in weeks 5 and 7 compared to the performance they had in week 3. From week 5 to week 7, no significant improvement was observed (Table 3).

When the condition difference is concerned, the results differ by time. In week 1, there are no significant differences between any of the conditions. However, in weeks 3, 5, and 7, the three conditions show pair-wise differences. From the estimates, participants in the DI condition showed the most accurate performance, while those assigned to the RE condition performed most poorly.

A further GLMM analysis of the melodies was conducted to investigate the effect that the different melodies (i.e., idiosyncratic versus standard) might have on the identification, and revealed no significant effect on type of melody observed in any of the training conditions ($p = .88$); however, group by melody and melody by instrument interactions were observed.

Upon further scrutiny, the interactions between melody and group showed that the effect of melody depended on group assignment. More specifically, participants in the DI group scored higher on the idiosyncratic melodies than on standard melodies ($p < .01$). This difference is displayed in Figure 2 where there is a clear difference between idiosyncratic and standard for DI in weeks 5 and 7. Individuals in the FB group scored higher on the standard melodies than on the idiosyncratic ($p = .03$) as shown in Figure 2, while RE showed no significant difference between the two melody types ($p = .24$).

Significant melody by instrument interactions were found for four instruments: clarinet, trombone, trumpet, and violin. Clarinet ($p < .01$), trombone ($p < .01$) and violin ($p < .01$) all had significantly higher levels of accuracy on the standard melodies (same melody used for all instruments) than on idiosyncratic melodies. Trumpet, however, had a significantly better performance on the idiosyncratic melody ($p < .01$) (see Figure 3).

Discussion

The purpose of this study was to compare three types of training conditions for timbre recognition. The results indicate not only that training can improve perception of a degraded signal of musical sounds but also that the type of training can influence the magnitude and rate of improvement. This study extends beyond prior studies of either acute training (e.g., Fu and Galvin, 2003; Pressnitzer et al, 2005; Li and Fu, 2007) or more extended training (e.g., Gfeller, Witt, Adamek, et al, 2002; Fu, Galvin, et al, 2005; Fu, Nogaki, et al, 2005) in illuminating what sort of input (e.g., feedback, direct instruction) is most effective as well as the minimum length of training required to achieve improvement. Thus, these data have implications for the amount of rehabilitation as well as type of training that is most likely to help CI recipients improve perception of one aspect of music listening: musical instrument recognition.

There is a difference among the three conditions over time, with the most effective as well as efficient (improvement across time) being those with some type of feedback or instruction. Even though the instrumental stimuli were identical for all conditions, repeated exposure without feedback showed no significant improvement while both feedback and direct instruction resulted in significant improvement. Direct instruction was the most effective with regard to magnitude and rate. It is heartening to see potential for significant improvement for timbre recognition as a result of three to five weeks of brief training sessions, as well as maintenance of benefit for at least two weeks following training.

It is important to note that all three conditions showed a significant improvement from the pretest (week 1) to the week 3 visit, though the magnitude of change for FB and DI in week 3 was significantly greater than RE. Furthermore, the FB and DI conditions continued to show improvement beyond week 3, while participants in the RE condition did not. This improvement in performance in the RE condition may be attributed to initial acclimatization, but the lack of additional improvement for RE is consistent with data from prior studies (Gfeller et al, 2008; Gfeller, Witt, Adamek, et al, 2002), which indicate that there is little improvement in timbre recognition as a matter of everyday listening experience and that incidental experience does not improve perception of music for the purpose of understanding in the same manner as that of speech (Tyler and Summerfield, 1996; Ruffin et al, 2007). The lack of improvement from mere exposure may be in part because the signal conveyed by the implant is less than optimal for transmitting the fine structure of the sound signal so important to music perception; thus

without specific input, the CI recipient does not get enough useful and discriminable information from the signal to acclimatize significantly as a result of everyday listening experiences alone. These results are consistent with prior studies (Gfeller, Witt, Adamek, et al, 2002), which indicate that timbre as a feature of music is amenable to rehabilitation but not as a matter of incidental exposure and more everyday experience with the CI. These simulation data are encouraging in that improvement occurred as a result of relatively brief training. However, it is clear that direct instruction results in more robust improvement than feedback alone and this improvement is maintained more effectively beyond the training period. An analysis of error patterns in the RE group revealed no specific patterns for recognition or error. However, responses from RE tended to display a random pattern similar to the initial test at week 1 with instruments selected incorrectly belonging within the same (or similar) frequency range rather than instrumental family (i.e., flute for violin, cello for trombone, etc.).

These results have implications for the sorts of information that should be included in auditory rehabilitation for timbre recognition. Because this training program did not include an appraisal component, we cannot presume that this type of training would result in significant improvement in enjoyment of sound quality. Future studies should address this matter because quality of sound is of considerable importance in music listening.

The finding that musical experience prior to testing had a significant effect is consistent with the research of Gfeller et al (2006, 2008), who found musical experience prior to hearing loss to be a predictor variable in success with music perception postimplantation. As a result, those individuals who have a musical past or have significant musical experience prior to their hearing loss may show a greater potential to improve music perception, with regard to timbre. While age was not found to be a significant predictor, the fact that it approached significance with a negative correlation to performance suggests that older persons may require more extensive or different forms of training to achieve similar benefit as younger adults.

It is also important to note that the same stimuli were included in all three training conditions yet the magnitude and rate of improvement were significantly greater for FB and DI, regardless of the specific musical stimuli presented. One rationale for the difference between the FB and DI conditions regarding the idiosyncratic versus standard melodies may be attributed to the various methods used by the participants. For the FB condition, the participants scored significantly better on the standard melodies rather than the idiosyncratic. This may be attributed to the use of the sound characteristics of each instrument for correct identification and trial and error, whereas the DI group may have learned the rhythmic properties of each idiosyncratic melody and associated them with their respective instruments; however, DI still performed significantly higher than FB on the standard melodies demonstrating recognition based on timbral properties as well.

This study shows how individuals with normal hearing improve their performance on CI simulations with training. Additional research is necessary to determine whether similar results would be obtained with recipients of CIs using similar instruction but with unfiltered sound stimuli. Comparisons between methods of reinforcement in future studies could include replacing the repeated exposure group with a modified feedback model where not only correct/incorrect information is provided but also the identification of the correct instrument. Future studies also should examine the effects of training for other key musical structures (e.g., melody, pitch) and combinations.

In summary, the analyses of these simulation data provide hope that recipients of CIs may be able to improve perceptual accuracy for at least one aspect of music listening with a relatively brief training protocol that can be delivered within their home environment.

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Abbreviations

CI	cochlear implant
DI	direct instruction
FB	feedback
GLMM	generalized linear mixed model
I/O	input/output
PAT	paired associate memory test
RE	repeated exposure

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Figure 1.
Percent correct for each group measured at each testing period. Standard error bars with one standard deviation.

Figure 2.
Progress over seven-week period for recognition of standard and idiosyncratic melodies in each condition.

Figure 3.

Percent correct of instruments on standard and idiosyncratic melodies. Brackets without point show instrument where idiosyncratic melody recognized significantly more than standard. Brackets with point show instruments where standard melody recognized significantly more than idiosyncratic.

Table 1
Cutoff Frequencies for Six-Channel Modulations

Channel	Cutoff frequency (Hz)
1	80 ~ 308
2	308 ~ 788
3	788 ~ 1794
4	1794 ~ 3906
5	3906 ~ 8338
6	8338 ~ 17640

Table 2
Tests of Fixed Effects

Variable	F Value	P value
Condition	16.28	<0.01
Week	305.03	<0.01
Music Experience	12.99	<0.01
PAT	0.88	0.35
Age	2.97	0.08
Gender	0.83	0.36
Known	0.57	0.45
Age by Condition	1.06	0.35
Condition by Week	42.99	<0.01

Table 3
Week Effect Comparisons for Each Group

Condition	Week	Estimates	P value
Repeated Exposure	1 vs. 3	-0.43	<0.01
	1 vs. 5	-0.40	<0.01
	1 vs. 7	-0.44	<0.01
	3 vs. 5	0.03	0.77
	3 vs. 7	-0.02	0.88
	5 vs. 7	-0.05	0.67
Direct Instruction	1 vs. 3	-2.03	<0.01
	1 vs. 5	-2.42	<0.01
	1 vs. 7	-2.37	<0.01
	3 vs. 5	-0.39	<0.01
	3 vs. 7	-0.33	<0.01
	5 vs. 7	0.05	0.58
Feedback	1 vs. 3	-1.56	<0.01
	1 vs. 5	-1.84	<0.01
	1 vs. 7	-1.76	<0.01
	3 vs. 5	-0.28	<0.01
	3 vs. 7	-0.20	0.03
	5 vs. 7	0.08	0.37

Table 4
Group Effect Comparisons for Each Week

Week	Conditions	Estimates	P value
Week 1	RE vs. DI	0.01	0.92
	RE vs. FB	-0.07	0.62
	DI vs. FB	-0.09	0.54
Week 3	RE vs. DI	-1.59	<0.01
	RE vs. FB	-1.21	<0.01
	DI vs. FB	0.38	0.01
Week 5	RE vs. DI	-2.01	<0.01
	RE vs. FB	-1.51	<0.01
	DI vs. FB	0.49	<0.01
Week 7	RE vs. DI	-1.91	<0.01
	RE vs. FB	-1.39	<0.01
	DI vs. FB	0.52	<0.01