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COGNITIVE EFFORT AND PERCEPTION OF SPEECH BY POSTLINGUALLY DEAFENED ADULT USERS OF COCHLEAR IMPLANTS

By

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ABSTRACT

COGNITIVE EFFORT AND PERCEPTION OF SPEECH BY POSTLINGUALLY DEAFENED ADULT USERS OF COCHLEAR IMPLANTS

By

Rana Anas Alkhamra

Cochlear implants (CIs) are remarkable devices that make functional hearing possible for users who would otherwise have only minimal access to sound. Postlingually-deafened adults who receive a CI often recover the ability to perceive speech. At the same time, the CI-processed speech signal that they receive lacks a number of acoustical features that are available to normally-hearing listeners. The present dissertation study tested the hypothesis that postlingually-deafened CI users must therefore make a greater-than-normal commitment of cognitive effort in order to achieve perceptual success when listening to speech. This hypothesis was tested in two ways.

In part one of the dissertation, a substantial group of postlingually deafened adult CI users (n=127) were surveyed. Survey participants rated the cognitive effort that they must expend when listening to speech in a wide variety of everyday circumstances. They also rated the effort needed at various points in time, both pre- and post-implant. Finally, they provided demographic information and information about hearing history, both of which were examined in relation to the cognitive effort ratings. Key findings included the following: (a) CI users reported experiencing a sharp reduction in the cognitive effort needed to perceive speech during the first days and weeks post-implant, and lesser but continuing reductions for several months thereafter; (b) the cognitive effort needed to perceive speech was reported to increase significantly whenever the level of background noise increased, when listening to an unfamiliar topic of conversation, when listening to an unfamiliar talker (or talkers), and when

listening to a non-native speaker or to a rapidly speaking talker; and (c) CI users who regularly wear a hearing aid in the opposite ear reported exerting significantly less effort than those who do not use a hearing aid.

Speech in background noise is widely reported to present particular difficulty for CI users. In the second part of this dissertation, an experimental study was therefore conducted to measure the cognitive effort needed to perceive speech depending on the level of competing background noise. Two groups of listeners were tested: Group CI were n=12 postlingually-deafened adults who had worn a CI for at least a year and who were rated as very good speech perceivers by their clinicians; Group NH were a comparison group of n=18 normally-hearing listeners. Results indicated that when listening in quiet and at a favorable signal-to-noise ratio (S/N) of +15 dB, the CI users were capable of maintaining substantial accuracy in their speech perception performance, nearly as high as that of NH listeners. However, significantly greater cognitive effort was required in order for the CI group to perceive speech in these conditions. When the background noise level increased to S/N=+5 dB, speech perception errors made by both groups increased, but they increased much more rapidly for the CI group. Also there was evidence of a substantially greater than normal commitment of cognitive effort to speech processing by members of the CI group. Finally, a comparison of results for a group of NH listeners tested at S/N = 0 dB and a group of CI users tested at S/N = +10 dB showed similarities in both their speech perception accuracy and their commitments of cognitive effort. Hence, the two groups could be roughly equated by a +10 dB change in S/N.

DEDICATION

To my father, mother and brothers
who have always believed

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CHAPTER 1

Introduction and Review of the Cochlear Implant Literature

In years past, hearing aids and tactile devices were the only treatment options available for persons with sensorineural hearing loss (SNHL). Today, many people with severe-to-profound hearing loss are able to receive benefit from cochlear implants (CIs). Many CI users perform well on speech perception tests especially when listening in quiet. They may also have the ability to use the telephone (Anderson, Baumgartner, Böheim, Nahler, Arnoldner, & D'Haese, 2006; Wilson & Dorman, 2008). However, there is considerable variation in treatment outcomes. This variation can be partially explained by differences among patients in cortical or auditory pathway function (Sharma, Dorman, & Spahr, 2002; Fallon, Irvine & Shepherd, 2008). The longer the period of auditory deprivation, the more challenging speech perception becomes for CI users (Blamey et al., 1996; Sharma et al., 2002; Summerfield & Marshall, 1995). Many studies have demonstrated that other factors such as age at the time of surgery, gender, duration of hearing loss, aetiology of hearing loss, residual hearing, implant type, speech processor strategy,and number of active implanted electrodes may also account for some but not all of the variability seen in adults and children (Blamey et al., 1993; Dowell, Dettman, Blamey, Barker, & Clark, 2002; Dowell, Hollow, & Winton, 2004; Gantz, Woodworth, Knutson, Abbas, & Tyler,1993; Geers, Brenner, & Davidson, 2003; Green el al., 2007; Rubinstein, Parkinson, Tyler, & Gantz, 1999; Summerfield, & Marshall,1993; Turner, Gantz, Vidal, Behrens, & Henry, 2004).

While many multichannel CI users perform very well when listening in quiet, listening to speech in a competing background noise remains a challenge. Speech performance can deteriorate rapidly with increasing levels of background noise, even for the most successful CI users (e.g., Fu & Nogaki, 2005; Friesen, Shannon, Baskent, & Wang, 2001).

Most studies that have investigated CIs to date have used standard audiometric tests of speech intelligibility to assess the listening abilities of children and adults with CIs. For example, they have measured the intelligibility of individual words or whole sentences (Beijen, Mylanus, Leeuw, & Snik, 2008; Cullington & Zeng, 2008; Riss, Arnoldner, Baumgartner, Kaider, & Hamzavi, 2008).

The present study was conducted with a different focus. Specifically, the cognitive effort required to achieve listening success was examined here. A number of previous studies have found that the cognitive effort needed to perceive speech can be affected by a listener's hearing status (Choi, 2005; Downs, 1982; Feuerstein, 1988; Hicks &Tharpe, 2002; Moore, 2003; McFadden & Pittman, 2008; Rakerd, Seitz, & Whearty, 1996; Rossiter, Stevens, & Walker, 2006). The present investigation extended this perspective to the assessment of persons with CIs.

This section provides background information about CIs. It discusses: what a CI is, the history of CI's, components of CI systems, candidacy criteria for receiving a CI, and speech perception findings regarding individuals with CIs. It also reviews factors that can influence speech perception by CI users such as time since implant, level of background noise, and talker-related variability.

Cochlear Implants

What is a cochlear implant?

Cochlear implants (CIs) are surgically implanted devices that can be used effectively by both prelingually-deafened children and postlingually-deafened children and adults. For persons with normal hearing, the outer and middle ears act as a bridge to transfer acoustic pressure changes present in the surrounding atmosphere to the fluids in the cochlea. Vibrations set up in the fluids then cause other structures within the cochlea to vibrate and to stimulate the sensory receptors known as hair cells (Martin & Clark, 2003).

The cochlea is organized so that the highest frequency sounds cause maximum stimulation of the hair cells at its base. The lowest frequency sounds cause maximum stimulation of the sensory cells at the other end, the apex of the cochlea (Moller, 2006; Von Bekesy, 1989). Thus, the information about the incoming sound is detected and passed onto the auditory nerve in a frequency-selected way. This organization of the hair cells and the auditory nerve is referred to as *tonotopic organization (*Rauschecker & Shannon, 2002). Information about sound is coded by the place in the cochlea and also by the timing patterns of how the nerve fibers respond to sounds (Estabrooks, 1998; Moore & Teagle, 2002; Tye-Murray, 2004).

People with hearing losses in the severe- to-profound range often have absent or malfunctioning sensory cells in the cochlea. CIs are designed to substitute for the functions of the outer, middle, and inner ears, transforming sound energy into electrical energy that directly stimulates the auditory nerve tonotopically. Specifically, electrical signals transmitted through implanted electrodes activate the auditory nerve tonotopically which begins the signal propagation in the nervous system. The neural signals are first passed in to the brain stem and then up to higher centers of the brain, ultimately reaching the auditory cortex (Allum, 1996; Rauschecker & Shannon, 2002).

History

The history of CIs began with Alessandro Volta in 1790, when he inserted metal rods into each of his ear canals and experienced a ''boom within the head,'' followed by a sensation of sound similar to that of ''boiling, thick soup.'' The more recent history began with the work of Djourno and Eyriès in Paris in 1957 (Niparko, 2009). They stimulated the hearing of a deaf adult by placing an electrode on the auditory nerve. The patient reported sensing the presence of environmental sounds but could not understand speech or discriminate among speakers or many sounds. Shortly after Djourno and Eyriès work, William House in Los Angeles (1961) was inspired by their work and initiated an effort to develop a practical and reliable way to treat deafness using electrical stimulation of the cochlea. By the 1980s, single-channel implants were in widespread use among adults with severe-to-profound hearing loss. By 1988, multichannel systems with multiplechannels of processing and with multiple sites of stimulation in the cochlea had come into use (Wilson & Dorman, 2008). In 1990, the Food and Drug Administration (FDA) approved multichannel CIs for children (Tye-Murray, 2004; Wilson & Dorman, 2008).

Components of implant systems

CI systems consist of both internal and external components. The external components include: a directional microphone, which picks up sound from the environment; a speech processor that filters, analyzes, and digitizes the sound signal into coded electrical signals; and a transmitter coil that transmits the signals across the skin to the implanted receiver via an FM radio signal. The principal internal component is a receiver that is surgically placed under the skin and is inductively coupled with the wearable transmitter (Owens & Kessler, 1998, Tye-Murray, 2004; Wilson & Dorman, 2008). This device receives the signal from the externally worn coil and delivers it to the electrodes in the implanted array.

The electrode array is a small wire that is inserted into the cochlea. Direct stimulation of the auditory nerve is produced by currents delivering the correct amount of electrical stimulation to one or more of the electrodes in the scalatympani. Most CIs today are multichannel devices, which mean that the electrode pairs in the electrode array present different information to different regions of the cochlea (Tye-Murray, 2004; Wilson & Dorman, 2008).

Candidacy criteria

Late-deafened adults are generally good candidates for CIs. Current Food and Drug Administration (FDA) candidacy criteria for adults 18 years and over are (a) severe-to-profound sensorineural hearing loss (SNHL) in both ears (>70 dBHL); (b) receiving little or no useful benefit from hearing aids; (c) scoring, with a hearing aid, 50% or less on sentence recognition tests in the ear to be implanted and 60% or less in the non-implanted ear or bilaterally; (d) desire to improve hearing and realistic expectations; and having (e) no medical contraindications (Cohen , 2004 ; "candidacy criteria", 2010; Copeland & Pillsbury, 2004; Zwolan , 2001).

Speech perception in individuals with cochlear implants

There is good evidence that both adults and children with severe-to-profound hearing loss can receive substantial benefits from CIs and attain high levels of open-set speech recognition (Moore & Teagle, 2002; Wilson & Dorman, 2008). Particularly relevant to the present study are the speech perception abilities of postlingually-deafened adults who receive a CI. A majority of these users can understand speech well (Lassaletta et al., 2005; Zwolan, 2001). Many implantees successfully return to their old jobs (Hamzavi, Baumgartner, Pok, Franz, & Gstoettner, 2003). However, despite all the benefits of CIs, many individuals still experience difficulty hearing in group situations and in background noise (Cullington & Zeng, 2008; Fu & Nogaki, 2005; Zhao, Stephens, Sim, & Meredith, 1997). A number of factors can affect the benefit and performance of adults using a unilateral CI. Several of these factors are examined in detail below.

Time since implant.

A number of studies have evaluated the impact of length of use of multichannel implants. Hamzavi et al. (2003) tested 66 late-deafened adults (36 females, 30 males; mean age 53.8 years; age range 19–78 years) using CIs. Tests were carried out at first fitting, after 3 months, 6 months, 12 months, and then annually for up to 6 years following implantation. Three speech perception tests were used in conducting the study. The Freiburger Numbers test is a test that is composed of four groups of 10 four-syllable numbers. The Freiburger Monosyllables test is composed of three groups of 20 everyday monosyllables. Both tests were presented to listeners at 70 dB SPL in free field, using a recorded voice of a male speaker. In the Innsbrucker Sentence Test (Hamzavi, Baumgartner, Adunka, Franz, & Gstoettner, 2000), one list of 10 three- to eight-word sentences was presented by the examiner himself at 65 dB SPL. Visual clues for lip-reading were not given. Repetition was not permitted in the three tests.

Results indicated that all participants showed a steady improvement over time on every test. Scores obtained after one month showed significant improvement over scores obtained at time of fitting for all tests ($p<0.05$). There was also significant progress on one or more of the tests between 1 and 3 months, 3 and 6 months and 6, and 12 months ($p<0.05$). After 12 months of use, testing showed some continuing but statistically insignificant improvement for the group as a whole. Many patients reached a plateau within the first 12 months.

Ruffin and colleagues (2007) found that speech perception abilities stabilize over a period of 24 months post-implant. All of the participants in their study (n=31) had postlingual profound bilateral SNHL and received no benefit from hearing aids prior to receiving a CI (the mean years of profound deafness were 8.8, and the mean age at implantation was 51).

Participants were evaluated at approximately 3, 6, 9, 12, and 18 months after initial stimulation, and annually thereafter. Participants were initially tested with the NU-6 Word lists and then later with the consonant-nucleus-consonant (CNC) word test as speech discrimination testing measures evolved. This study treated both word lists as identical test items because no significant differences between NU-6 and CNC words were found. Data used in analysis were from one of three possible sources: the CNC score when this was the only test given to the subject at that time point; the NU-6 score when this was the only test given; the average of the two test scores when both tests were given to the subject at the same point in time.

The most significant performance gains occurred in the first 9 months with slower improvement from 9 to 24 months. After 24 months post-implantation, there was no significant growth or decline in speech perception unless adverse medical events were experienced. Age at implantation was significantly and substantially negatively correlated with most scores over all tested periods. There were no age-related declines in performance.

Another study by Oh et al. (2003) targeted evaluation of long-term speech perception of cochlear implantees and compared the developing auditory performance patterns of prelingually-deafened children and postlingually-deafened adults. The study included 29 children and 17 adults who had been followed for four years. Speech perception ability was assessed using tests of vowel and consonant confusion and the Korean version of the Central Institute of Deafness test (K-CID) (performed without visual cues). The K-CID test assesses understanding of speech in everyday conversational situations. Test results were analyzed at three and six months after implantation and then annually. In the prelingually-deafened children, the average results continued to improve over the four year period. In postlingually-deafened adults, improvement did not extend beyond the first two years post-implantation. Adults with < 5 years of deafness had a faster rate of recovery of speech perception than those who had been deaf for > 5 years.

Lastly, in a study by Taina et al. (2000), questionnaires were completed by three

Hearing Centers in Finland. Participants in the study were 67 adults (mean age 47 years). The mean duration of profound hearing loss prior to CI was 13 years (range 0–51 years). Data were pooled to present the following evaluation intervals: preoperative, 0–3, 4–6, 7–11, 12–23, and 24 months post-implantation. After three months of implant use, the CI users' mean word recognition score was 54% correct. Scores improved steadily over the succeeding intervals, and after 24 months the mean word recognition score was 71% correct. Six months after switch-on, the majority of participants (48/67) were able to recognize some speech without speechreading, and 26 of the 48 participants were able to use the telephone with a known speaker, gaining good functional benefit from the CI.

Overall, results from the studies reported here provide evidence of improving speech perception for the first one to two years post-implant for postlingually-deafened adults, and little or no further improvements (or declines) thereafter.

Level of background noise.

Gifford et al. (2008) noted that hearing with CIs has advanced to the point that it has become difficult to track changes in patient performance over time because many patients achieve 90 to 100% scores on standard tests of sentence intelligibility in quiet (28% of the participants in their study achieved perfect scores). They therefore called for new, more challenging tests of intelligibility. The need for such tests speaks to the progress made in CI designs during the past two decades. Despite this progress, the current devices still do not restore normal speech perception when listening to speech in competition with noise. Compared to normal-hearing listeners, CI users have tremendous difficulty understanding speech in noise and their speech perception performance deteriorates rapidly with increased levels of background noise, even for the best CI users

(Friesen, Shannon, Baskent, & Wang, 2001; Fu & Nogak, 2005; Muller, Schmidt, & Rubert, 1995; Nelson, Jin, Carney, & Nelson, 2003). Loss of low-frequency detailed information in the speech signal and limitations on the number of effective channels of stimulation due to overlap in electric fields of the implanted electrodes are factors that are believed to lead to this deterioration in performance in noise (Wilson & Dorman, 2008).

When individuals with CIs decide to undergo surgery, the decision comes with a trade-off of losing any residual low-frequency hearing that may be present in the ear of implant. The residual acoustic hearing is no often longer usable, and only electric stimulation is available. Many CI users report after the initial device activation that: (a) the perception of sound becomes ''mechanical' when compared to the acoustic hearing they had before the surgery, and (b) many of the aesthetic qualities of sound are diminished (Turner et al., 2004). This loss of aesthetic quality may be related to a decrease in the ability to perceive the pitch information of sounds (Gfeller et al., 2002). The loss of pitch perception is primarily a consequence of the limited spectral resolution of current CIs (Cullington & Zeng, 2008; Gfeller et al., 2002; Turner, Reiss, & Gantz, 2008).

Present designs and placements of electrodes for CIs supports 8 or slightly more functional channels regardless of the number of electrodes (Henry & Turner, 2003). In comparison, the number of channels is about 39 for the full range of frequencies from 50 Hz to 15 kHz, and is about 28 for the range of frequencies covered by speech sounds (Niparko, 2009). These numbers are much higher than the number of effective channels available with a CI.

Fu and Nogaki (2005) conducted a study on sentence recognition by CI users (n=10) and by normally-hearing (NH) participants (n=6) in the presence of steady or modulated speech-shaped noise. Participants were native speakers of English. All CI users were tested using their everyday speech processor and they were instructed to use their everyday volume and microphone sensitivity settings and disable any noise-reduction settings in their speech processors. CI users listened to combined speech and noise (unprocessed) through their speech processors.

For NH participants, speech and noise were processed by an acoustic simulation of a CI. In the acoustic simulation, NH listeners were tested for different degrees of spectral resolution (16, 8, or 4 channels) and different degrees of spectral smearing (carrier filter slopes of -24 or -6 dB/octave). The signal was introduced at 65 dBA. During testing, NH participants listened to combined speech and noise processed by CI simulations. They also listened to unprocessed speech and noise for baseline measures.

Speech test material consisted of sentences taken from the Hearing in Noise Test (HINT) sentence set (Nilsson et al. 1994). Speech-shaped noise was used as a masker. The onset of noise was 500 ms before the sentence presentation and the offset of noise was 500 ms after the end of the sentence presentation; masker rise and fall times were 5 ms.

Results revealed that NH listeners' performance was significantly affected by the noise conditions. The poorest performance was observed with steady-state noise and improved with gated modulated noise. In CI users, no significant main effect of noise conditions was noted in their performance.

With modulated noise, NH listeners experienced significant release from masking (i.e., compared to steady-state noise) when the original unprocessed speech was presented. CI users, on the other hand, experienced no release from masking. As the spectral resolution was reduced, NH listeners' release from masking gradually diminished. Release from masking was further reduced as the degree of spectral smearing increased even when the spectral resolution was relatively high (eight channels).

In summary, regardless of the type of noise, CI users' speech recognition was negatively affected by the loss of spectro-temporal fine structure caused by the limited number of electrodes and spectral channels in the speech processing strategy. However, the number of spectral channels may not completely account for the poorer performance of CI users in noise. Spectral cues transmitted by the limited number of implanted electrodes are further reduced by the degree of channel interaction between electrodes. Findings suggest that implant users' susceptibility to noise may be caused by the reduced spectral resolution and the high degree of spectral smearing associated with channel interaction.

To facilitate hearing in noisy situations for CI users, combined electric and acoustic stimulation of the auditory system for patients with significant residual hearing in the low frequencies has been developed. To provide electric acoustic stimulation (EAS), an electrode is only partially inserted into the cochlea in order to preserve the residual acoustic hearing that many patients still have for low frequencies (Gantz & Turner, 2003; Turner el al., 2004; Wilson, Lawson, Muller, Tyler, & Kiefer, 2003).

Relatively normal hearing ability at low frequencies, with excellent frequency resolution and other attributes of normal hearing, may be preserved by EAS. EAS can

also provide a complementary representation of high frequency sounds with the CI and electrical stimulation.

In summary, studies agree that speech performance deteriorates rapidly with increased levels of background noise. Overall, listening in challenging situations, such as speech presented in competition with noise or other talkers, tend to be challenging to most CI users. Possible causes for the reduced performance in noise include reduced spectral resolution from a limited number of channels, interactions between channels, and loss of low-frequency information.

Talker-related variability.

Conditions that introduce variability into the speech signal include differences between talkers, changes in speaking rate, and dialectal variations (Pisoni 1993). In normally-hearing individuals, it is generally assumed that spoken word recognition includes some type of perceptual normalization process in which listeners compensate for signal variability and hence derive a more idealized internal representation of speech sounds (Pisoni, 1993; Pisoni & Luce, 1986; Takayanagi, Dirks, & Moshfegh, 2002). Whether and how listeners with hearing loss cope with variability is the subject of continuing investigation.

Kirk et al. (1997) investigated the consequences of talker variability on the word-recognition performance of listeners with hearing loss. Participants in Kirk's study (9 males, 8 females) were between the ages of 29 and 66 years (M=55 years). All had mild-to-moderate bilateral SNHL and showed speech recognition scores of 80% or higher. All participants had postlingually acquired hearing loss; nine of the participants used amplification. Speech recognition performance was assessed with the NU-6 test and Modified Rhyme Test (MRT).

Results from the study showed that word recognition performance was consistently lower in multiple-talker conditions (where the listener had to continually adjust to between-talker differences), than it was in a single-talker condition. Moreover, the participants' performance in the multiple-talker condition correlated more strongly with self-reports of communication ability than performance in the single-talker condition. A second finding was that performance was lower for speech produced at a fast speaking rate than for slower or normal speaking rates.

Results from a study by Takayanagi and Moshfegh (2002) were consistent with the Kirk et al. (1997) study. This study examined the effects of talker variability on spoken-word recognition among four groups of listeners: native speakers with normal hearing, native speakers with moderate SNHL, non-native speakers with normal hearing, and non-native speakers with SNHL.

The stimuli for the experiment included 75 lexically easy and 75 lexically hard words. Ten talkers (5 men, 5 women) produced each word while speaking at a normal conversation level. Participants were instructed to repeat the word heard after each presentation. The ability of listeners to accommodate variations in the talkers' voice was assessed by comparing recognition scores for a single-talker condition to those obtained in a multiple-talker condition.

Results revealed that participants with hearing loss, both native and non-native, required higher threshold sound pressure levels to reach 50% correct performance levels than their respective counterparts in the normal-hearing groups. Likewise, the hearing loss groups of non-native participants required significantly higher sound-pressure levels for 50% correct performance levels than the hearing native participants. The overall difference in performance between the normal-hearing and hearing-loss participants was greater than the difference between the native and nonnative participants. Furthermore, there was a performance difference between the hearing-loss groups and the normally-hearing groups in single vs. multiple-talker and easy vs. hard word tested conditions. Performance of the normally-hearing groups was superior to that of the hearing-loss groups in all tested conditions.

In the field of CIs, a few studies have addressed the impact of talker variability on speech perception performance. A study by Chang and Fu (2006) investigated the effects of talker variability on vowel recognition by cochlear implant (CI) users and by normal-hearing (NH) participants listening to 4-channel acoustic CI simulations. Six postlingually deafened CI users (4 men and 2 women; aged 47–71 years) were tested with their clinically assigned speech processors. For the 8 NH participants (4 men and 4 women; aged 26–37), 3 CI processors were simulated using different combinations of carrier type and temporal envelope cutoff frequency (noise band/160 Hz, sine wave/160 Hz, and sine wave/20 Hz). Vowel recognition was measured using a 12-alternative, closed-set identification procedure. The 12 phoneme tokens included 10 monophthongs and 2 diphthongs, presented in a /h/vowel/d/ context (e.g., heed, hid); which were drawn from speech samples collected by Hillenbrand, Getty, Clark, and Wheeler (1995). Test stimuli were presented in either a single-talker context (1 talker per test block) or a multi-talker context (4 talkers per test block), at 65 dBA.

Results indicated that CI users' vowel recognition was significantly poorer in the multi-talker context than in the single-talker context. When noise-band carriers were used in the simulations, NH performance was not significantly affected by talker's variability. However, when sine-wave carriers were used in the simulations, NH performance was significantly affected by talker's variability in both envelope filter conditions. The investigators concluded that because the fundamental frequency was not preserved by the signal processing, both spectral and temporal cues contributed to the talker variability effects observed with sine-wave carriers. Similarly, spectral and temporal cues may have contributed to the talker variability effects observed with CI participants. This area of study needs further investigation to explore effects of talker related variability on CI users' speech perception performance in everyday listening conditions.

Telephone use.

Speech perception by CI users has been extensively investigated for the special and important case of talking on the telephone. Telephone use can be difficult for CI users in part due to the limited frequency bandwidth of telephone signals (Liu, 2009). Other issues include lack of access to visual cues (no lip-reading) and fewer available contextual cues for the conversation (Anderson et al., 2006). Despite these limitations, many CI users can initiate calls to familiar speakers, answer the telephone, and identify a person's gender and age over the telephone. Understanding can become more difficult as the topic and speaker become more unfamiliar (Cray et al., 2004; Faber & Grontved, 2000).

Anderson et al. (2006) evaluated the use of both landline and mobile phones in an international sample of CI users. Results from 196 surveys obtained in 10 different countries (Austria, South Africa, United Kingdom, United States of America, Argentina, Belgium, Canada, Germany, Greece, and India) showed that there is a significant shift from preoperative non-use of a telephone to use of a telephone postoperatively. Talking to familiar speakers about familiar topics was found to be the easiest listening condition on the telephone, and it was easier to recognize a voice using the landline. Many respondents found it difficult to make a call without some assistance. Most participants could manage to call someone in an emergency, even on a mobile phone.

For reasons noted above, talking over the telephone presents some challenges not faced when talking to a person directly. CI users may vary in their ability to meet these challenges.

A survey study

Chapter 2 below reports the outcome of a survey of postlingually-deafened adult CI users. The survey asked for self-reports regarding the cognitive effort needed to perceive speech under various circumstances. Of particular interest were survey questions regarding each of three factors that were reviewed in this section: (a) time since implant; (b) background noise; and (c) talker-related variability.

An experimental study

Chapter 3 reports the outcome of an experiment that explored the cognitive effort that must be expended by a cochlear implant user when perceiving speech in quiet and in noise.

CHAPTER 2

A Cognitive Effort Survey

Part one of the present study is a survey that was given to a broad cross-section of postlingually-deafened adults who use CIs. The individuals surveyed were native English speakers and consistent CI users. The survey investigated their self-perceptions regarding the cognitive effort needed when perceiving speech under a variety of listening conditions. This chapter presents the methods and results of the survey, and discusses the implications of those results.

Methods

Survey instruments, or questionnaires, are used to collect data about subjects' demographics, personal histories, knowledge, behaviors, and attitudes (Passmore, Dobbie, Parchman , & Tysinger, 2002) . Mode of survey presentation is one of the first decisions to be made in designing and conducting a survey. Choices are essentially between interviewer administration (i.e. face-to face or by telephone) or self-administration by the respondent (i.e. postal delivery to one's home) (McColl et al., 2001). Self-administered surveys, distributed by mail or email, can provide respondents with privacy and anonymity (McColl et al., 2001; Passmore et al., 2002). However, these surveys typically yield numerous unusable or incomplete responses and may require multiple mailings to obtain adequate response rate (Passmore et al., 2002).

A self-administered survey that assessed cognitive effort in everyday life listening situations was employed in this study. Postlingually-deafened adults who had been wearing a CI for at least 6 months were asked about their listening experiences with the device. The survey highlighted the cognitive effort required when perceiving speech.

The section below outlines the steps taken to develop, test and administer the survey instrument. Methods followed in developing the present survey were based on findings of other studies or opinions of experts who have found certain strategies to increase response rates and minimize bias (Burns et al., 2008; Edwards et al., 2002; Dillman, 1995).

The Survey Instrument

The current survey (see Appendix A) was specifically developed for this study. A description of how the survey was designed and conducted is presented here. The discussion includes the following topics: survey domains, question construct, response format, appearance, consistency questions, pilot testing, and survey administration.

Survey domains.

The first step in the survey was item generation, the consideration of all potential items or questions for inclusion in the questionnaire, with the goal of introducing domains that help answer the research question (Kirshner & Guyatt, 1985). Three major domains were examined (a) cognitive effort when using a CI; (b) hearing history; and (c) demographics.

Cognitive effort.

This domain contained 16 questions that were subdivided as follows. Question, 1-5 asked about the participant's personal perception of cognitive effort pre-implant and at various intervals post-implant (in a week, and in 3-6 months or longer). Question 6a-6s investigated the participant's own perception of cognitive effort in various listening situations (in quiet vs. in low, medium and high noise levels; environmental vs. speech background noise; familiar vs. unfamiliar conversation topic; familiar vs. unfamiliar single talker; familiar vs. unfamiliar group of talkers; slow vs. fast talker; non-native English talker vs. native English talker; and familiar vs. unfamiliar talker on the phone). Questions 7- 8 investigated listening when engaged in a simultaneous task (e.g., taking notes, or driving a car). The possible advantage of using the hearing aid at the ear opposite to the implanted ear was explored in questions (9- 10). Questions 12 -14 were geared toward lipreading effects on speech listening. The last questions (15-16) were about how often participants communicated with familiar vs. unfamiliar talkers.

Hearing history.

The hearing history domain included questions 17-27. Question 17-18 investigated the etiology of hearing loss (i.e., sudden or progressive). Questions 19- 20 focused on the age at which the hearing loss was diagnosed and when the loss reached a level of severe-to-profound in both ears. Questions 21-23 included age at initial hearing aid use, how often the hearing aid was used prior to getting the CI, and how often the hearing aid was used in the ear opposite to the implanted ear. Questions 24-25 investigated the ear of implant (i.e. right vs. left) and duration of implant use. Vision status was the focus of questions 26-27.

Demographics.

This domain included questions 28-31. It posed questions about age, whether English was a participant's first language, level of education and employment status.

Questions construct.

When constructing the survey questions, the main goal was to develop a query that respondents would interpret similarly and respond to accurately (Dillman, 2000). Therefore, considerable pilot work to refine wording and content was required to generate the survey questions (Rattray & Jones, 2007).

Each question in the survey was composed of a "stem" and a "response format." The stem is the question that requires a response and the response format provides a framework for subjects' answers (Passmore et al., 2002). The wording of stems was developed to be short - fewer than 20 words, and simple and easy to understand and interpret (Stone, 1993). Simple vocabulary was used to make sure that it could be understood by most people. Ambiguity was avoided (Burns et al., 2008), and the stem wording was developed to mean the same thing to both the respondent and the inquirer (Stone, 1993). Also, an equal number of positive and negative categories for the scalar questions was used to convey that disagreement is an acceptable answer (Dillman, 2000).

Questions were asked one at a time (Passmore et al., 2002) and double-barreled questions were avoided (Dillman, 2000). Double-barreled questions contain two components that require one answer, but about which a respondent may think differently (e.g., Do you wear a hearing aid with the CI and use it all the time?). There is evidence that item non-responses are more frequent for these types of questions (Bowling, 1997). Consideration was given to the order in which items and domains were presented. For example, to engage participants and prevent boredom, demographic and/or clinical questions were presented at the end of the survey (Rattray & Jones, 2007).

Response format.

Response formats used in the survey were both closed and open. An open response format allows subjects to answer a question in free text (questions 17, 19, 20, and 21). Closed-response formats give subjects a structured way to answer items by requiring the subject to choose from a list of options (Passmore et al., 2002) (questions 1-16, 22-27, and 29-30). Questions 25 and 30 were partially-closed ended and several response categories were listed while allowing respondents to add other answers (Dillman, 2000).

Answers were generally provided in a 5-point Likert-type scale. The traditional Likert scale, with a statement as a stem followed by responses ranging from strongly disagree to strongly agree, is commonly used in surveys (Passmore et al., 2002) . The Likert- type format used in the *cognitive effort* domain measured attitude towards cognitive effort when listening in different conditions in terms of being effortful/effortless (strongly effortful, somewhat effortful, neither effortful or effortless, somewhat effortless, strongly effortless and no opinion) (questions 1- 8). The likert-type response scale (all the time, most of the time, some of the time, rarely and never) was used when respondents were asked to rate the frequency with which they use a hearing aid in conjunction with a CI (questions 9), lipreading (questions 12-13), and communication with familiar/unfamiliar speakers (questions 15-16). In the *hearing history* and *demographic* domains, other response formats such as open-ended answers (questions 19-21 and 28) and yes/no answers (questions 29) were provided. See Appendix A.

Survey appearance.

The questionnaire was printed as a booklet (i.e. on sheets of paper folded, and stapled through the spine). This format is recommended by survey experts (e.g. Dillman, 2000; Sudman, & Bradburn, 1982), as it provides ease in reading and turning pages, and reduces the risk of losing pages. Also Bourque and Fielder (1995) suggested that a booklet presented a more professional appearance.

Creating visual navigational guides to assist respondents in adhering to the prescribed navigational path and correctly interpreting the written information was considered in the appearance of the survey construction. Dillman (2000) suggested a number of aspects such as using dark print for questions and light print for answer choices, separating optional or occasionally needed instructions from the question statement by font or size variations, and using simple answer boxes for recording answers. Survey experts also agreed that vertical answer formatting is easier than the horizontal formatting for self-completing the survey (Bourque & Fielder, 1995; Dillman, 2000; Sudman & Bradburn, 1982).

Instructions were placed where needed and not at the beginning of the questionnaire (Bourque & Fielder, 1995). Following Dillman's (2000) recommendation, text was organized so that the question, associated instructions and response categories all appeared on a single page. He also recommended instructions regarding how the answer questions should be provided to distinguish instructions from the question distinctive format of printing (e.g., using upper case or italics). Instructions of skip patterns were given to respondents to guide them to the appropriate questions. Special attention was given to the front cover of the survey that contained, as recommended by

Dillman (2000) and Sudman et al. (1995), the title of the survey (which should convey its purpose in an interesting but neutral manner), a graphic illustration, and brief instructions.

Consistency questions.

Consistency is important to test reliability and validity (Fowler, 1995). Fowler (1995) indicated that a way to measure the consistency of survey questions is simply to ask the same person the same questions twice, generally with minor differences in wording. Inconsistent answers to the same questions, are considered to be evidence of invalid reporting. In the current survey, two consistency questions (question 4 and 6o) were presented. The first consistency question (question 4) "After using your cochlear implant for six months or longer, did listening to speech become more or less effortful than it was before the implant?", represented a consistency check when compared to question 5, "Did speech listening become more or less effortful when you became more accustomed to hearing speech with your cochlear implant?". The second consistency question (question 6o), "How effortful or effortless is listening to someone using English as a first language" was compared to question 6q, "Did speech listening become more or less effortful when listening to someone using your native language?"

Pilot testing.

The questionnaire was pre-tested with a group of users to ensure respondents comprehended questions as intended in the study by carrying out cognitive interviews. Cognitive interviewing is a technique that is used to determine whether respondents comprehend questions as intended by the survey sponsor and whether questions can be answered accurately (Dillman, 2000). There are two main cognitive techniques: think aloud interviewing and probing. In the think-aloud approach the respondent is asked to think-aloud while completing the questionnaire, whereas the probing method involves the investigator asking questions or probes to elicit how the respondent went about answering the question. In the think-aloud approach, respondents concurrently describe what they are thinking and answer the survey questions. Probing can be used either concurrently or retrospectively (Collins, 2003). In the current survey both methods were used to elicit answers and feedback from respondents. These techniques were effective in identifying whether respondents understood the questions in a consistent way. Questions reported by respondents to be a problem were either deleted or reworded.

Survey administration.

A review by Heberlein and Baumgartner (1978) showed that the total number of contacts (including both prenotification and follow-up) had the strongest impact on response rates. More recent reviews (Edwards et al., 2002) and experts in the field of survey methodology (Dillman, 2000) also agreed that it is important to make multiple contacts and that the total design method should involve four contacts in total: the prenotification initial mailing and up to three follow-ups.

In the present study, initial contact with respondents was via a simple, personalized cover letter that was mailed with the questionnaire. The cover letter content included thanking the subject for answering the questionnaire questions, explaining the purpose of the survey, explaining why that person was chosen to complete it, and why that person's participation was important to the study. A stamped, self-addressed pre-paid envelope was included with the questionnaire. Respondents were requested in the cover letter to complete and return the survey questionnaire in the pre- paid envelope.

Edwards and colleagues (2002) reported that sending a personalized contact letter with the questionnaire, sending the questionnaires by first class post, and providing a pre-paid return envelop are associated with increased response rates. Each questionnaire was assigned a serial number to ensure security of the contacted names and to keep track of who returned the survey and who did not.

Two to four weeks after mailing the questionnaire, a follow-up contact was attempted. A follow-up contact letter and a replacement questionnaire were mailed to participants who did not respond. The follow up letter indicated that the person's completed questionnaire had not been received and urged the recipient to respond. Nakash and colleagues (2006) identified, in a systematic review of 15 randomized trial reviews in health research that reminder letters have a favorable impact on response rates. Regarding the increase in response rate from making multiple contacts, Edwards and colleagues (2003) reported similar results in their systematic review.

The questionnaire, cover letter, and second contact letters were approved by the Institutional Review Board (IRB) of the University of Michigan and Michigan State University prior to mailing. Contact letters were printed on letterhead stationery of the Department of Communicative Sciences and Disorders, Michigan State University.

Results and Discussion

Questionnaires were mailed to 260 prospective participants soliciting information on cognitive effort, demographics, and hearing history. Out of the 260, 138 participants (53%) responded to the survey. Of the 138 respondents, 88 were female (63%) and 51 were male (37%). Surveys returned by 12 of the respondents (1 male, 11 females) were excluded from further analysis because of inconsistent responses to the "consistency questions" (see the survey instrument section above), or because there was other clear evidence that the user had misunderstood the survey instructions. Hence the present report is based on an analysis of the survey answers provided by 127 participants.

There was a total of 31 questions on the survey, several with multiple parts. Appendix A provides descriptive statistics regarding the participants' responses to all of these questions. The focus of this dissertation – and the focus of a set of analyses reported in this chapter – was on responses given to a subset of questions that assessed perceived cognitive effort in relation to three factors of primary interest: (a) time since implant; (b) level and type of background noise; and (c) talker-related variability. Aspects of the participants' hearing history and demographics that may have influenced their responses to questions regarding these three primary factors were also considered here.

Participants

Survey participants were accessed from the University of Michigan CI Program patient database. All identified participants had received their CIs and subsequent therapy through the University of Michigan CI program. Prospective participants had received a unilateral CI and had used the device for more than 6 months.

Demographics.

All of the participants were native speakers of English and ranged in age from 23-90 years (mean=63). Of the 127 participants who responded to the survey, 69 (54%) were ≤ 60 years old, 54 (43%) were > 60 years, and 3% were age anonymous.

Education level varied widely between participants and was distributed as follows: elementary school (2%), junior high school (2%), high school (or vocational high school) (29%), some college (34%), or 4 years of college (13%).The highest level of education was more than 4 years of college (16%). Only (1%) of the participants did not identify their level of completed education.

Employment status also varied substantially. Participants were either employed (25%), unemployed (6%), owned their own business (4%), students (2%), retired (54%) or involved in other roles (8%). As in education, (1%) of the participants did not give their employment status.

Hearing history.

Hearing loss onset and duration of deafness. The participants reported that their hearing loss (whether sudden or progressive) was identified as severe-to-profound as early as year 1 and as late as year 86 (mean=42 years). Duration of deafness ranged between 0-65 years (mean=21). Of the 127 participants, 27 (21%) reported having a sudden hearing loss and a 100 (79%) reported having a progressive hearing loss (i.e. worsened over time).

Etiology of hearing loss. The most common etiologies of hearing loss reported included heritable causes (syndromic, non-syndromic), noise exposure, meningitis, enlarged vestibular aquaduct, ototoxic drugs, head trauma, Meniere's disease, chronic ear infection, viral disease, nerve deafness, and otosclerosis. The rest of the participants reported deafness of unknown cause. Table 2-1 gives a frequency count of the etiologies of hearing loss across the 127 participants.

Table 2-1. *The etiologies of hearing loss across participants.*

Etiology of HL	No. of participants	Average percentage
Heritable	32	26%
Noise exposure	7	6%
Meningitis	7	6%
Ototoxic drugs	1	1%
Enlarged Vestibular aquaduct	2	2%
Head Trauma	3	2%
Meniere's disease	1	1%
Chronic ear infection	1	1%
Viral disease	11	9%
Nerve deafness	13	10%
Otosclerosis	1	1%
Unknown	48	38%
Total	127	100%

Hearing aid use before implantation. The median age at which participants received a hearing aid before implantation was 29 years; the average for 1 - 81 years. Most participants used their hearing aid in the implanted ear all the time (61%). Other participants used their hearing aids most of the time (8%), some of the time (3%), rarely (5%) or never (21%). Of the participants, 2% gave no response to this question. Participants using a hearing aid in the opposite ear used a hearing aid prior to CIs all the time (54%), most of the time (6%), some of the time (3%), rarely (6%), or never in their life (31%). The question was not responded to by 2% of the participants.

Hearing aid use after implantation. After implantation, only 14% of the participants reported using a hearing aid in the opposite ear all the time, 3% most of the time, and 2% some of the time. In comparison, the highest percentage (75%) reported never using a hearing aid in the opposite ear post-implant. The rest of the participants (3%) reported rarely using a hearing in the opposite ear. Only a few participants (2%) did not respond to this question.

Ear of implantation. Slightly more participants (54%) had a right ear implantation compared to the 44% who received an implant in the left ear. The remaining 3% gave no response to this question. What might explain the higher percentage of implant in the right ear is the right ear advantage (REA). For more than 50 years, the REA has been reported in the auditory processing literature (Gadea, Espert, & Chirivella, 1997). The left hemisphere is dominant for speech and language processing and the contralateral auditory pathways are stronger. Therefore, when sound from the right ear is sent to the left hemisphere (via contralateral pathways) a right ear advantage is often apparent in speech, language, and dichotic presentations of language-based sounds, particularly in younger people (Tadros et al., 2005; Henkin et al., 2008).

CI use. All participants had been using their CIs for a period longer than 6 months. Specifically, 4% of the participants have been wearing the device for 7-12 months, 9% for 13-18 months, 5% for 19-24 months and 80% for more than 2 years. Only 2% of the participants did not report length of time they have been using their device.

Cognitive Effort Questions

Response rate.

The present analysis focused on 20 self-evaluation questions regarding cognitive effort. Table 2-2 lists the response rate to each of these questions. The response rate was 90% or above for all but one question (Question 6s). In that instance, there was an 88% response rate. The average response rate for all 20 cognitive effort questions was 97%.

Table 2-2. *Summary of cognitive effort response rates (based on 127 survey participants)*

Question focus	# of Responses	%
Before CI	124	98%
1st Week after CI	119	94%
3-6 Months after CI	125	98%
>6 Months after CI	124	98%
Quiet	123	97%
Low noise	125	98%
Medium noise	126	99%
High noise	125	98%
Familiar topic	124	98%
Unfamiliar topic	126	99%
Familiar talker	123	97%
Unfamiliar talker	124	98%
Familiar group	125	98%
Unfamiliar group	126	99%
Familiar talker on phone	114	90%
Unfamiliar talker on phone	112	88%
Slow talker	124	98%
Fast talker	125	98%
Native English talker	122	96%
Non native English talker	117	92%
Average	123	97%

"No Opinion" rate.

Answers to the cognitive effort questions were given on a 6-point scale. Steps 1-5 of the scale gave self-ratings of cognitive effort needed when performing a particular listening task. Step 6 was a "no opinion" option. The "no opinion" option was available to respondents who felt they could not rate cognitive effort for a particular situation.

Table 2-3 reports the frequency of "no opinion" responses given to each cognitive effort question and related statistics. Figure 2-1 shows a plot of "no opinion" response rate.

Table 2-3. *Summary of "No Opinion" reports for each of the cognitive effort questions.*

Question focus	# of Respondents	# Reporting no-opinion	%
Before CI	124	3	2%
1st week after CIs	119	8	7%
3-6 weeks after CIs	125	2	2%
> 6 months after CIs	124	3	2%
Quiet	123	4	3%
Low noise	125	2	2%
Medium noise	126	1	1%
High noise	125	2	2%
Familiar topic	124	1	1%
Unfamiliar topic	126	1	1%
Familiar talker	123	4	3%
Unfamiliar talker	124	1	1%
Familiar group	125	1	1%
Unfamiliar group	126	1	1%
Familiar talker on phone	114	9	8%
Unfamiliar talker on phone	112	10	9%
Slow talker	124	2	2%
Fast talker	125	1	1%
Native E. talker	122	3	2%
Non native E. talker	117	12	10%
Average	123	4	3%

Respondents who gave "no opinion" for a question were excluded from any statistical analysis associated with that question. Table 2-3 shows that the number of exclusions of this kind was small, typically <5% (mean=3%). The largest "no opinion" rate for any question was 10% (question 6p). The rates of 3 other questions (2, 6r, 6s) were also relatively high (2= 7 %, 6r= 8%, 6s= 9%).

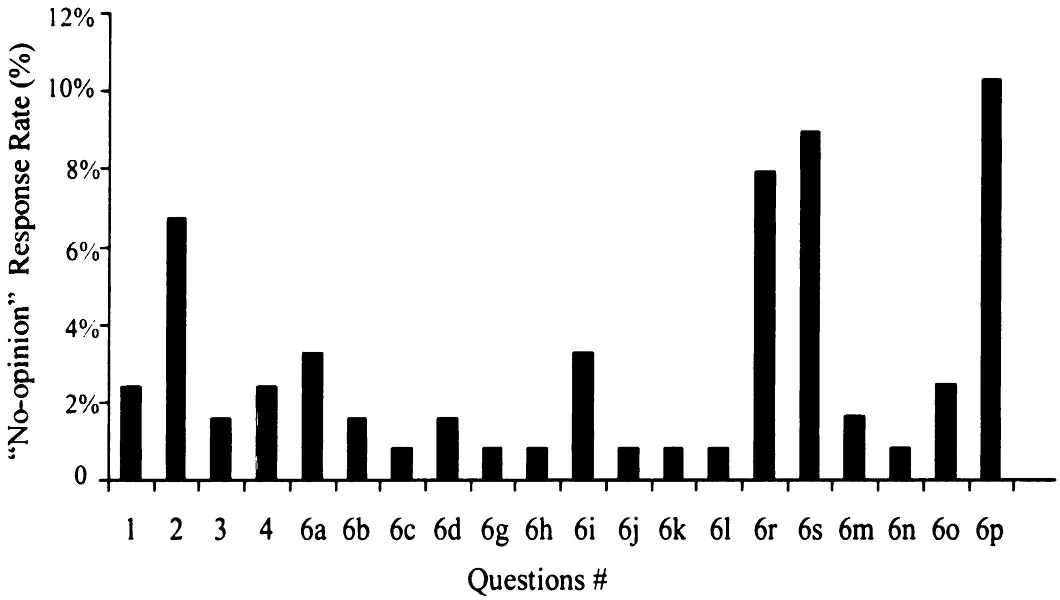

Figure 2-1. Percentage of "no opinion" responses given to the cognitive effort questions.

The rating scale: data coding.

The five response options for cognitive effort rating were as follows: strongly effortful, somewhat effortful, neither effortful nor effortless, somewhat effortless, and strongly effortless. For the present study, those options were assigned numbers on a 5-point scale of increasing effort as follows:

"Strongly effortless" was coded as "1" and is referred to here as "low" effort.

"Somewhat effortless" was coded as "2".

"Neither effortful nor effortless was coded as "3" and is referred to as "mid".

"Somewhat effortless" was coded as "4".

"Strongly effortful" was coded as "5" and is referred to as "high" effort.

Data Analysis – cognitive effort questions

Respondents' ratings regarding cognitive effort, calculated on this 5-point scale, were the primary data for this study. Means and standard deviations for various conditions are reported graphically (and compared statistically) throughout this chapter. Figure 2-2 provides an example of the format for graphical presentation. Responses are shown for two questions about perceived cognitive effort, effort "before CI" (prior to implant) and "1 week after CI" (one week post-implant). The mean response "before CI" was 4.73 (S.D. = 0.78) which represents "high" effort, near the maximum possible perceived cognitive effort on this scale. This compares to a mean rating of 2.35 (S.D. =1.22) for cognitive effort needed just "1 week after CI".

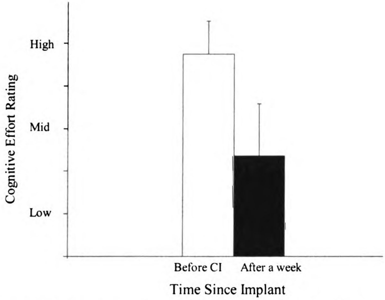

Figure 2-2. Cognitive effort before receipt of the cochlear implant and one week post-implant (mean and standard deviation).

Repeated measures analysis of variance (RM-ANOVA) was used to analyze the results of this study (SPSS software) (Field, 2009). Most factors in the analyses (described below) were binary, i.e. they had only two levels. There were, however, several factors with 3 or more levels. In such cases, there is potential for overestimation of statistical significance due to violation of the "sphericity" assumption of RM-ANOVA. The Greenhouse-Geisser correction takes this into account and reduces the degrees of freedom in the statistical analysis accordingly (Field & Hole, 2003). The Greenhouse-Geisser correction was used throughout this study, whenever three or more levels of a factor were analyzed.

Time since implant.

As discussed in Chapter 1 (see Time Since Implant section) a number of previous studies have provided evidence of improving speech perception for the first 1-2 years post-implant for postlingually-deafened adults using multichannel CIs. Typically, no further improvements or declines in speech perception are seen thereafter.

The current study participants were asked to rate their cognitive effort when listening to speech at each of 4 points in time: before implant, one week post-implant, after 3-6 months, and after more than 6 months. Figure 3 shows the results. Perceived cognitive effort before implant (Question 1) was reported to be extremely high (mean = 4.73, S.D. = 0.78). After a week of CI use (Question 2), the perceived effort score was substantially reduced (mean = 2.35, S.D. = 1.22). After 3-6 months post-implant (Question 3) the effort was reduced further (mean= 1.62, S.D. = 0.88). Finally, after 6 months (Question 4) the effort rating was reduced to its lowest reported value (mean = 1.40, S.D. = 0 .78).

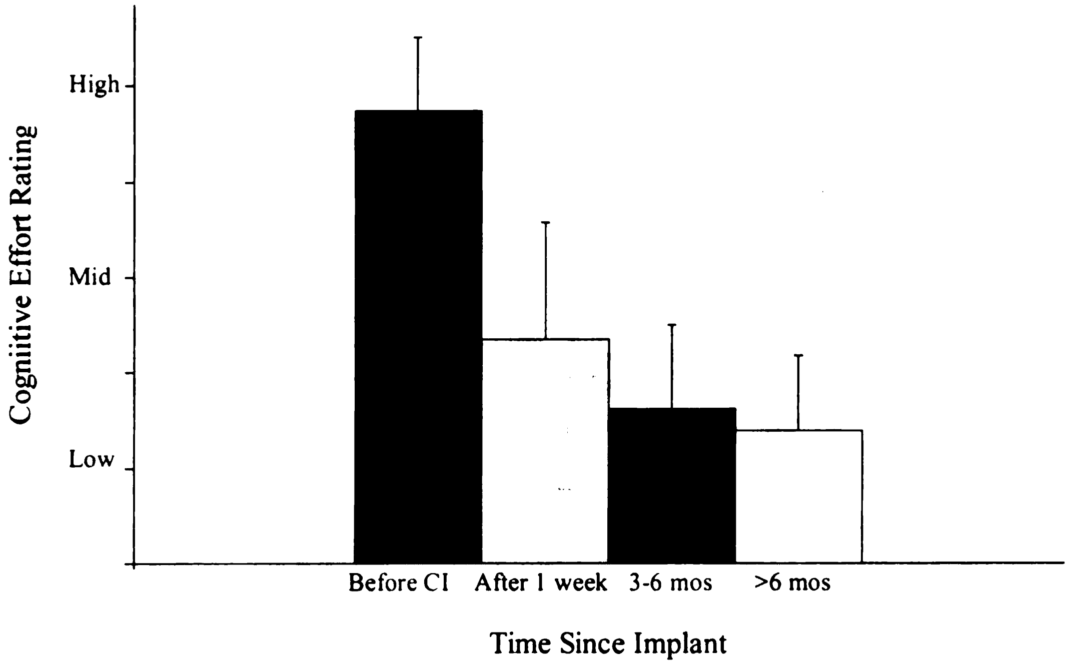

Figure 2-3. Cognitive effort and time since implant.

A statistical analysis of the results shown in Figure 2-3 found a highly significant main effect of time since implant (F (2.43, 281.82) = 342.23, P<.0001). To examine differences between the individual means, Bonferroni-corrected post-hoc tests (paired *t-tests*) were conducted. Table 2-4 shows the results of these tests, conducted on time-adjacent intervals (e.g., before implant vs. one week after). Comparison 1 reported in this table (before implant vs. one week after) shows that participants experienced a significant reduction in cognitive effort immediately post-implant. Comparison 2 shows that further significant reduction in cognitive effort was experienced after 3-6 months. Finally, there was no significant difference between the mean effort scores reported at 3-6 months and > 6 months. Overall, the pattern of results found here shows a marked reduction in cognitive effort immediately post-implant and some further reduction in effort over the first 6 months as the users accommodate to listening with a CI.

Table 2-4. *Pairwise comparisons between adjacent time since implant means (Bonferroni-protected t-tests).*

Time since implant comparison	Mean difference	SE	Significance
Before vs. After a week	2.41	0.14	0.0001
After a week vs. After 3-6 months	0.74	0.10	0.0001
After 3-6 months vs. After >6 months	0.19	0.09	0.173

These self-report results generally correspond well with previous studies of speech perception which indicate that the greatest improvement in speech perception performance takes place during the first 6 months post-implant (Hamzavi et al. 2003; Oh et al., 2003; Ruffin et al., 2007; VaLimaa & Sorri, 2001). Speech perception often continues to improve after 6 months; whereas, no significant improvement in cognitive effort was reported here beyond 6 months. In other words, these results indicate that improvement in cognitive effort takes place somewhat faster than it does in speech perception, and may asymptote after 6 months of implant use.

The largest improvement seen here took place in just a week post-implant. Hence, consistent with a number of other reports (e.g., Hamzavi et al., 2003), the participants here reported immediate and dramatic improvements in listening post-implant. What perhaps explains this immediate improvement in cognitive effort in postlingually-deafened adults are the top-down listening skills in speech and language that they had developed prior to deafness. Top-down listening skill involves a listener's ability to bring previous information to bear on the task of understanding the "heard" language (Morley, 2001). This may enhance the immediacy of improvement, as reported here. In summary, results indicated a dramatic reduction in perceived cognitive effort immediately post-implant and continuing improvements thereafter over approximately the first 6 months post-implantation.

Background noise.

Studies have agreed that speech performance deteriorates rapidly with increased levels of background noise for CI users (See chapter 1, speech perception section). Overall, listening to speech in competition with noise, especially noise from other talkers, is challenging for most CI users. A CI listener cannot gain an advantage in distinguishing among multiple talkers by perceiving their different voice pitches (Nelson et al., 2003; Stickney, Zeng, Litovsky, & Assmann, 2004) and this inhibits their ability to understand target speech (Nelson et al., 2003). Other contributing factors include limited frequency resolution with an implant and possibly spectral "smearing."

The present study assessed CI users self-perceptions of the effort required to perceive speech under various background noise conditions. Specifically, participants were asked to rate cognitive effort for each of four levels of background noise: quiet, low noise, medium noise, and high noise (Questions 6a, 6b, 6c, and 6d). The results are shown in Figure 2-4. In quiet, cognitive effort was reported to be low (mean =1.55, S.D. = 1.04). In low background noise, cognitive effort was higher than in quiet (mean = 2.13, S.D. = 1.13). In medium background noise, cognitive effort increased to the mid-level (mean = 3.07, S.D. = 1.25), and cognitive effort was given its highest rating (mean = 4.26, S.D. = 1.12) in high background noise.

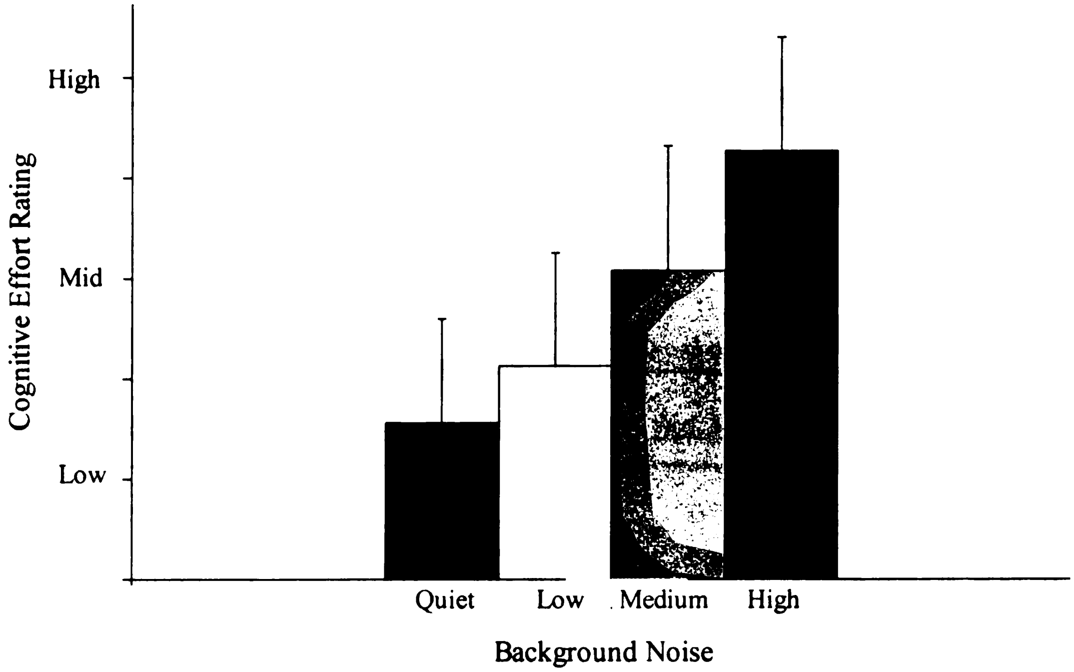

Figure 2-4. Cognitive effort ratings for listening in quiet and in three different levels of background noise.

Overall, there was a highly significant main effect of background noise on cognitive effort (F (2.16, 259.14) = 273.79, *P*<.0001). This is consistent with numerous speech perception studies which have reported background noise to have a negative impact on speech recognition performance in adults using CIs. The presence of background noise reduces the intelligibility of a target talker's speech and at the same time increases the need for the listener to apply top-down strategies to compensate. The present findings show that CI users are conscious of this cognitive demand and sense that it becomes increasingly great when the noise level increases (and the signal-to- noise level decreases).

Table 2-5 reports post-hoc tests between all adjacent means shown in Figure 5. All of the pairwise differences were statistically significant beyond p<0.001. The present results are consistent with Fetterman and Domico's (2002) speech perception study, in which speech recognition scores were found to be significantly different between different background noise levels. Clearly, the current survey participants were aware of the perceptual challenges posed by increasing levels of background noise.

Table 2-5. *Pairwise comparisons between adjacent noise level means.*

Background noise comparison	Mean difference	Std. Error	Significance
Quiet vs. Low	-0.57	0.06	0.0001
Low vs. Medium	-0.96	0.09	0.0001
Medium vs. High	-1.21	0.10	0.0001

Noise type.

Participants were also asked to compare the cognitive effort required when listening in background noises of different types. Specifically, they compared *speech noise* to *environmental noise*. Numerous speech perception studies have reported that the more similar the spectral characteristics of a masking noise are to the speech signal, the greater is the masking effect (Hygge, Ronnberg, Larsby, & Arlinger, 1992; Larsby & Arlinger, 1994). Participants in the current study were asked to rate cognitive effort when background noise was environmental (e.g., car horn) and when there was speech noise (e.g., multiple talkers in a restaurant). Results are shown in Figure 2-5. Ratings for the two noise types were similar, although the effort rating was slightly and statistically significantly higher for the speech noise ($F(1, 124) = 8.32$, $P<0.0005$). Apparently, the users are aware of somewhat greater cognitive challenges when the background noise is speech. However, the high effort rating for both noise types (speech: 4.0, environmental: 3.78) point up their general difficulty when dealing with background noise of any kind.

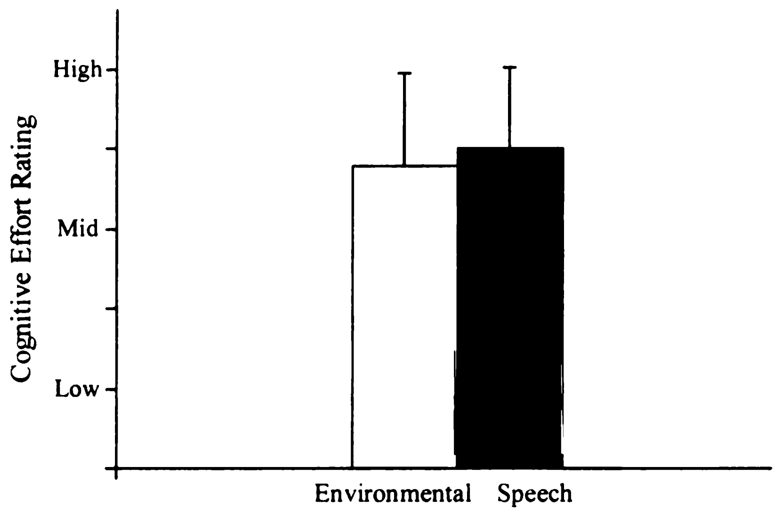

Figure 2-5. Cognitive effort for listening in environmental vs. speech background noise.

Talker-related variability.

Physical differences between talkers introduce variability into the speech signal. Variability also results from changes in the speaking rate and from the speaker's language history (native vs. non-native speaker). In the current survey, a participant's perception of the importance of talker related variability was investigated. Specifically, participants were asked to rate cognitive effort according to (a) the "familiarity" of topic and talker, and (b) "speaking characteristics" of the talker (fast vs. slow talker, native vs. non-native talker).

Familiarity effects.

Possible effects of familiarity on cognitive effort were evaluated. Specifically, participants were asked whether there was a perceived difference between listening in a familiar condition vs. the corresponding unfamiliar condition. The results for a series of comparisons are given below.

Familiarity of topic. Participants were asked to rate cognitive effort when listening to a familiar topic (question 6g) vs. an unfamiliar topic (question 6h). Figure 2-6 shows the results. Cognitive effort was reported to be within the low-mid range (mean = 2.60, S.D. =1.26) when listening to a familiar topic. Cognitive effort increased significantly ($F(1,123) = 135.58$, $P < .0001$) to the high-mid range (mean response= 3.60, S.D. =1.22) when the topic was unfamiliar.

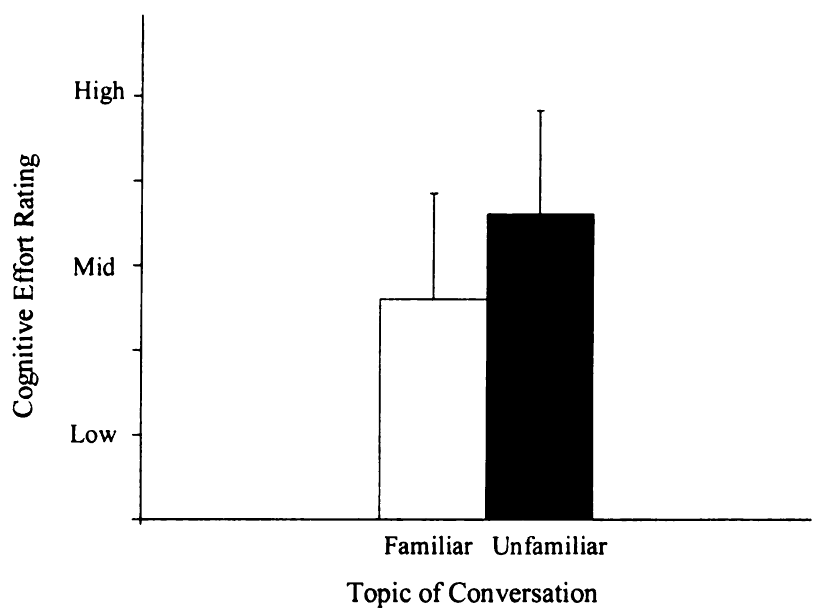

Figure 2-6. Cognitive effort and level of familiarity of the conversation topic.

A few perceptual studies (e.g., Tye-Murray & Tyler, 1988) have examined the impact of topic familiarity on performance in individuals with hearing loss. These studies have documented that unfamiliar content is more difficult to perceive than familiar content. Results from the current study agree with those results.

Familiarity with one or more talkers. Cognitive effort was rated when listening to a single familiar talker (Question 6i) vs. a single unfamiliar talker (Question 6j), and when listening to a familiar group of talkers (Question 6k) vs. an unfamiliar group of talkers (Question 6l). Results are given in Figure 2-7. Cognitive effort was reported to be at the mid range when listening to an unfamiliar talker (mean = 2.63, S.D. =1.21) and to substantially decrease, to the low range (mean = 1.79, S.D. =1.13), when listening to a familiar talker. Similar results were reported in the case of listening to a group of talkers. Cognitive effort was at the high-mid range when listening to an unfamiliar group (mean = 3.90, S.D. =1.16) and decreased to the lower-mid range (mean = 3.28, S.D. =1.28) when the group was familiar.

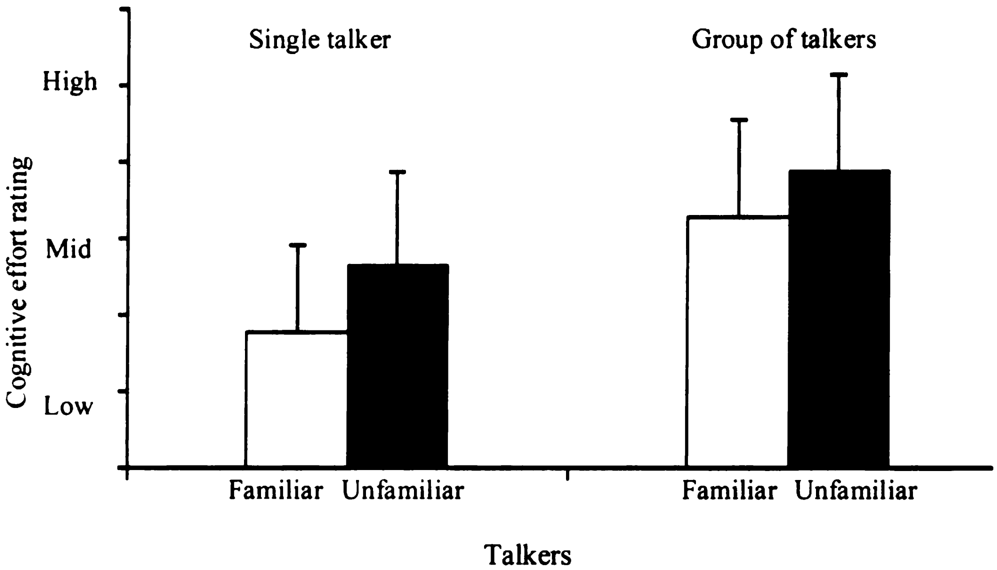

Figure 2-7. Cognitive effort results when the talkers were known (familiar) or unfamiliar.

Analysis of the results shown in Figure 2-7 revealed significant main effects of talker familiarity (familiar vs. unfamiliar) ($F\ (1,120) = 94.35$; $P<.0001$), and number of talkers (single talker vs. group of talkers) ($F\ (1, 124) = 54.68$, $P<.0001$) on cognitive effort. These results indicate that postlingually deafened CI users exert more cognitive effort when listening to an unfamiliar talker (or talkers) than when listening to a familiar talker, and when listening to a group of talkers than when listening to a single talker. Present findings agree with results from previous studies (Bradlow, & Pisoni ,1999; Kirk, Pisoni, & Miyamoto, 1997; Takayanagi, & Moshfegh, 2002) that report word recognition performance to be consistently lower in multiple-talker conditions than in single-talker conditions, in adults with mild-to-moderate hearing loss. Also, word recognition scores were reported to be superior in familiar (single /group) conditions than in unfamiliar (single/group) conditions.

Talking on the telephone. Familiarity regarding a talker on the telephone was also rated. Results are given in Figure 2-8. When talking on the phone to an unfamiliar talker (question 6s), cognitive effort was reported to be in the high-mid range (mean = 3.77, S.D. =1.29). In comparison, when the telephone talker was familiar (question 6r), cognitive effort reduced to the low-mid range (mean = 2.74, S.D. =1.49).

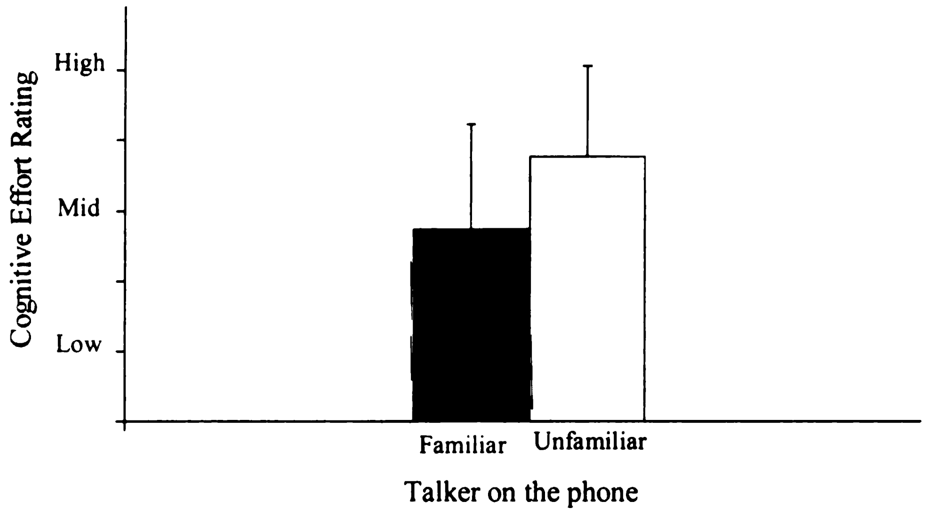

Figure 2-8. Cognitive effort results regarding familiarity of talker on the phone.

Statistical analysis of the results in Figure 2-8 indicated a significant main effect of familiarity of talker on the phone ($F(1,110) = 751.36$; $P<.0001$) on cognitive effort. Cognitive effort tends to increase on the telephone, particularly when listening to an unfamiliar talker. These results correspond with results from other CI studies (Cray et al., 2004; Faber & Grontved, 2000) that found understanding of conversation on the telephone to be more difficult as the topic and speaker become more unfamiliar. A lack of access to visual cues, as well as the phone's limited frequency bandwidth, causes understanding speech to be more difficult on the telephone in general. These factors appear to exaggerate the difficulty.

Speaking characteristics of a talker.

Cognitive effort was also evaluated in the current study according to the following characteristics of a talker: rate of speech *(slow vs. fast talker)* and native language *(native vs. non-native English speaker)*. Results of these comparisons are presented in Figure 2-9. Cognitive effort was reported to be low (mean = 1.85, S.D. =1.13) when listening to a slow talker and considerably increased when listening to a fast talker (mean = 3.57, S.D. =1.23). Also, cognitive effort was indicated to be in the low-mid range when listening to a native English speaker (mean = 2.16, S.D. =1.25) and to increase substantially (mean = 3.79, S.D. =1.14) when listening to a non-native English speaker. Both of these differences were statistically significant: speaker rate ($F\ (1,123) = 951.78$; $P<.0001$), and native language ($F\ (1,113) = 188.12$; $P<.0001$).

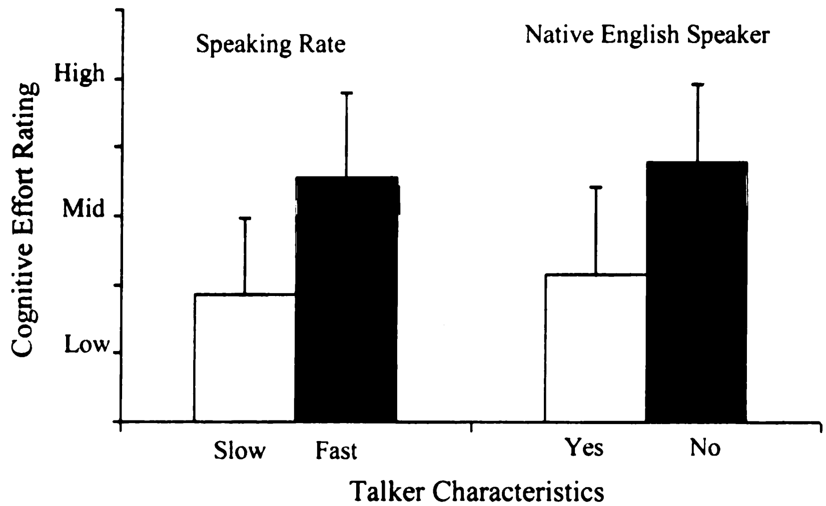

Figure 2-9. Graph of cognitive effort results according to the talker characteristics.

These findings are consistent with results from prior studies (e.g., Bradlaw & Pisoni; 1999; Kirk et al., 1997) that reported word recognition scores to be lower for speech produced at a fast speaking rate compared to a slower or normal speaking rate for adults with hearing loss. The present results indicate that CI individuals are consciously aware that they must expend extra effort when listening to fast speakers or non-native speakers.

Additional Factor Questions

There is a good deal of variability among CI users regarding their ability to perceive speech post-implant. All of the following factors have been reported to account for some portion of that variability: (a) gender, (b) age, (c) cause of hearing loss, (d) duration of implant use, (e) ear of implant, and (f) using hearing aid in the opposite ear post-implant (Gifford, Dorman, McKarns, & Spahr, 2007; Green et al., 2007; Hamzavi et al., 2003; Henkin et al, 2008, Morrell et al., 1995; Tyler et al., 2002; Van Dijk et al., 1999). The present study asked whether any of these factors might also explain some of the variability among survey participants regarding their cognitive effort reports. In a series of analyses reported below, these factors were first tested for possible main effects, and second tested for possible interactions with other cognitive effort factors.

For each of these factors, participants were divided into subgroups based on their responses to survey questions 9, 18, 24, 25, 26, 28. Table 2-6 shows the participant counts in each subgroup.

Table 2-6. *"Other Factors" subgroups sizes.*

Variables	Subgroup 1	Subgroup 2
Gender	Males (n=51)	Females (n=87)
Age	≤ 60 years (n=54)	> 60 years (n=69)
Hearing loss onset type	Sudden (n=27)	Progressive (n=100)
Uses a hearing aid in the opposite ear	Yes (n=28)	No (n=96)
Duration of implant use	≤ 2 year (n=22)	> 2 years (n=102)
Ear of implant	Right (n=67)	Left (n=55)

Data Analysis- additional factors questions

Main effects tests.

The purpose of the investigation here was to look for trends in the survey data that may be investigated further in future research. With that in mind, any statistical test with a significance level of $p \leq 0.25$ was identified here as providing evidence of a ***significant trend*** in the data.

"Best" Conditions.

Survey responses to the following questions were averaged together to get a combined test-estimate of a participant's cognitive effort rating when listening in situations that might be expected to be the "*best*" and hence least challenging:

Question 4: After using your cochlear implant for six months or longer, did listening to speech become more or less effortful than it was before the implant?

Question 6a: How effortful or effortless is listening in quiet settings?

Question 6g: How effortful or effortless is listening to a familiar conversation topic?

Question 6m: How effortful or effortless is listening to someone who speaks slower than normal?

Question 6o: How effortful or effortless is listening to someone using your native language?

Question 6r: How effortful or effortless is listening to someone familiar on the phone?

Table 2-7 gives the rating results for each subgroup regarding listening under these "*best*" conditions. The rightmost column highlights instances of significant trends.

Table 2-7. *Mean cognitive effort rating when listening under the "Best Conditions".*

Variable	Subgroup 1	Subgroup 2	Difference	T-value	P-value	Significant trend
Gender	Males 2.20	Females 1.89	0.31	2	0.05	*
Age	≤ 60 yrs 1.88	> 60 yrs 2.10	-0.22	-1.39	0.17	*
Hearing loss onset	Sudden 2.22	Progressive 1.94	0.28	1.51	0.13	*
Uses a hearing aid in the opposite ear	Yes 1.95	No 2	-0.04	-0.28	0.81	
Duration of implant	≤ 2 yrs 1.90	> 2 yrs 2.02	-0.13	-0.63	0.53	
Ear of implant	Right 1.99	Left 2.05	-0.06	-0.39	0.70	

Significant trends in the data were found for three factors when listening under these best conditions. Those factors were: gender, with female participants reporting lower effort than male participants; age, with younger participants reporting lower effort than older participants; and hearing loss onset type, with progressive onset participants reporting reduced effort compared to sudden onset participants. Although significant, these effects were also small, resulting in mean rating differences of 0.31 or less. Hence it can be concluded that each of these factors had a small but consistent impact on the participant ratings for listening in everyday situations that presented minimum challenges.

"Worst" Conditions.

Responses to the following questions were averaged to obtain an effort rating when listening under the "*worst*" conditions:

Question 2: During the first week after getting your cochlear implant, did listening to speech become more or less effortful than it was before the implant?

Question 6d: How effortful or effortless is listening in high level noise settings?

Question 6h: How effortful or effortless is listening when unfamiliar with the conversation topic?

Question 6j: How effortful or effortless is listening in a one-to-one conversation with an unfamiliar speaker?

Question 6n: How effortful or effortless is listening to someone who speaks faster than normal?

Question 6p: How effortful or effortless is listening to someone with a foreign accent?

Question 6s: How effortful or effortless is listening to someone unfamiliar on the phone?

Table 2-8 gives the rating results for listening under these "*worst*" conditions.

Table 2-8. *Mean cognitive effort rating when listening under the "Worst Conditions".*

Variable	Subgroup 1	Subgroup 2	Difference	T-value	P-value	Significant trend
Gender	Males 3.50	Females 3.39	0.11	0.71	0.48	
Age	≤ 60 yrs 3.38	60 yrs 3.48	-0.09	-0.63	0.53	
Hearing loss onset	Sudden 3.54	Progressive 3.40	0.14	0.81	0.42	
Uses a hearing aid in the opposite ear	Yes 3.10	No 3.52	-0.42	-2.46	0.02	*
Duration of implant use	≤ 2 yrs 3.25	> 2 yrs 3.48	-0.23	-1.21	0.23	*
Ear of implant	Right 3.49	Left 3.40	0.09	0.64	0.53	

Trends were found for two factors when rating listening under the worst conditions. The first factor was use of a hearing aid in the opposite ear post-implant. Those who used a hearing aid had effort ratings significantly lower than those who did not. This was the largest effect found here (mean difference= - 0.42). It was also statistically significant at the 0.02 level. Several interaction analyses reported below also indicate that listening with a hearing aid in the opposite ear can be especially helpful under challenging listening conditions. These results agree with findings from other studies that have documented gains from binaural hearing. Using a CI combined with a hearing aid in the opposite ear can lead to improved sound localization, improved speech discrimination in noise, and improved overall sound quality (Dunn, Tyler, & Witt, 2005; Tange, Grolman, & Dreschler, 2009).

The second factor that had a significant trend here was duration of implant use, with those who had worn an implant for ≤ 2 years providing a slightly lower rating (-0.23) when compared to those who had worn the implant for more than 2 years. This trend was not confirmed in any of the subsequent interaction analyses.

Interactions between the Additional Factors and the Primary Factors

This chapter began with detailed analysis and discussion of three factors that were of primary interest in this study: time since implant, background noise level (and type), and talker-related variability. This section reports on a series of ***interaction*** analyses that were conducted to ask whether any of the additional factors listed in Table 2-6 may have interacted with any of the primary factors, and hence may offer added perspective on their interpretation. Two-way repeated-measures ANOVAs were conducted for all combinations of the additional factors and the primary factors. A significant trend was defined statistically as any instance in which the *F*-test of the interaction had an associated significance level of 0.25 or less. A total of 10 significant trends were found. They are listed in Table 2-9 and examined individually below.

Table 2-9. *Interactions for which there was statistical evidence of a significant trend. The significance level of the interaction F-test is reported here.*

	Time since CI	Back-ground noise	Talker familiarity	Telephone partner familiarity	Rate of speech	Native Lang-uage
Age	0.03			0.09		
Gender		0.12				0.07
Hearing loss onset					0.13	0.03
Uses a hearing aid in the opposite ear.		0.13	0.013	0.07	0.04	

Reduced effort in a favorable listening condition.

Four significant interaction trends were found that showed the following pattern: Lower cognitive effort reported by one subgroup compared to another when perceiving speech in a relatively favorable listening condition, but little or no difference between the groups when the listening became more challenging. The four interactions that took this form were: gender and speakers' native language; age and telephone talker familiarity; hearing loss onset type and speakers' native language; and hearing loss onset type and rate of speech. These interactions are pictured in Figures 2-10 through 2-13.

Paired *t-tests* confirmed significant differences in cognitive effort between subgroups as follows: females had lower cognitive effort than males when listening to a native talker ($t(120)= 2.516$, $p<.013$) ; younger CI users had lower cognitive effort than older users when listening to a familiar talker on the telephone ($t(109)= -2.819$, $p<.006$) ;

hearing loss when listening to a native speaker (t(122)= 1.97, $p<.051$) as well as when listening to speech produced at a slow rate (t(120)= 1.922, $p<.057$). All four of these trends were consistent with results from main effects tests that indicated generally better performance by the corresponding subgroups when listening under "best" listening conditions (see main effects section above).

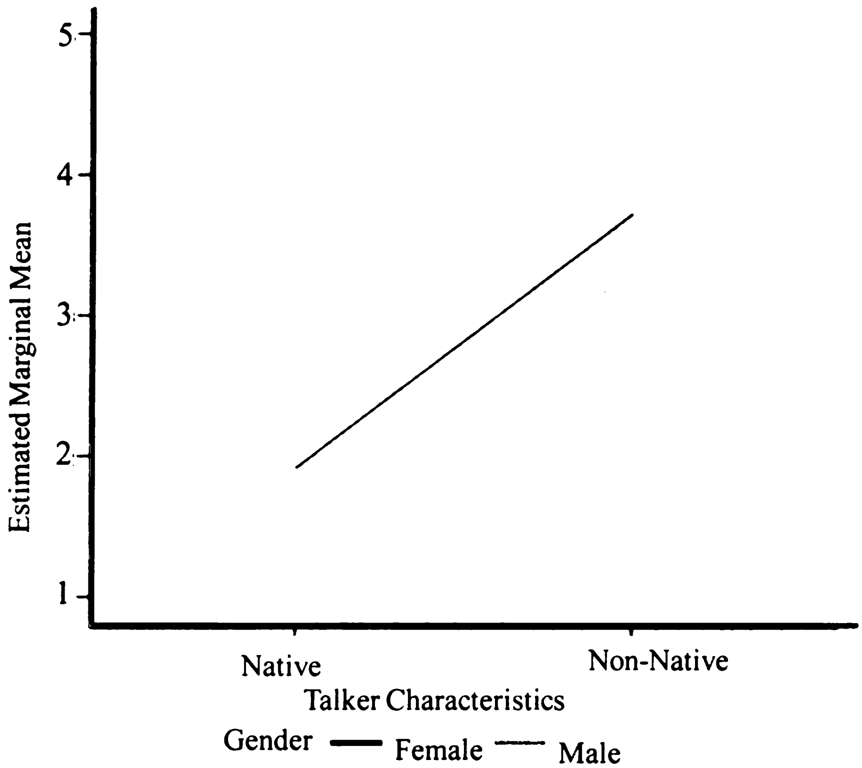

Figure 2-10. Interaction between CI users' gender and talkers' native language (native vs. non-native speaker of English).

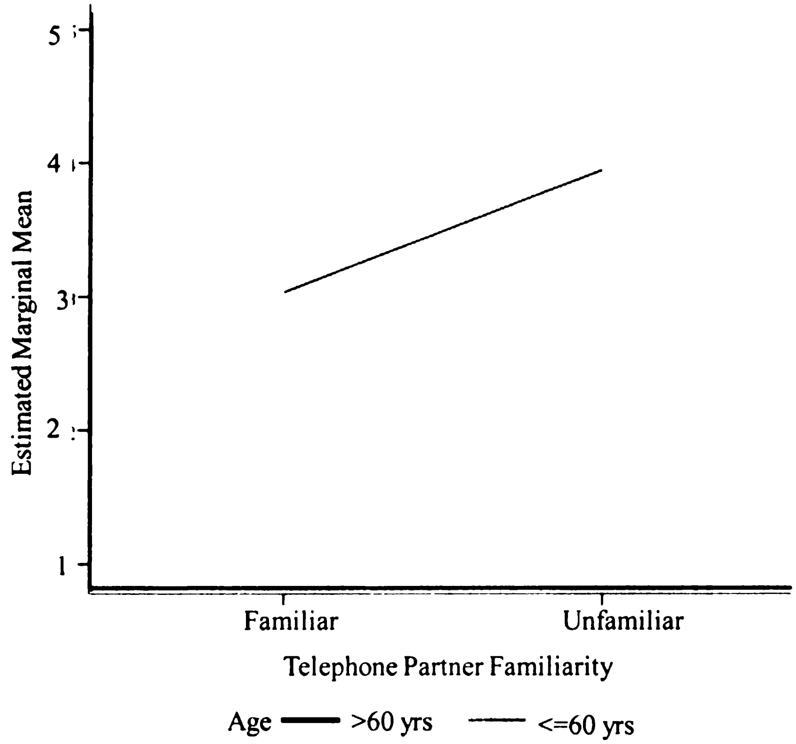

Figure 2-11. Interaction between CI users' age and telephone partners' familiarity.

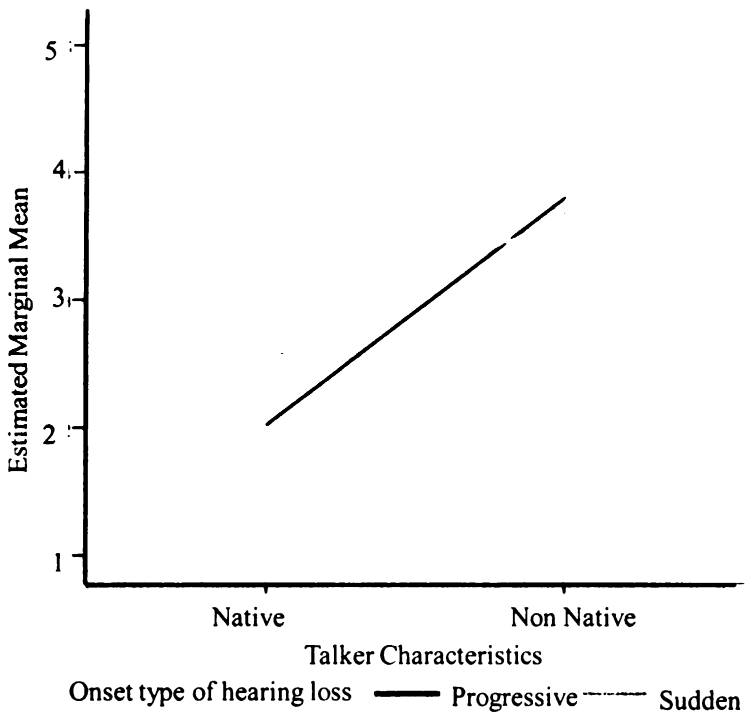

Figure 2-12. Interaction between hearing loss onset type and talkers' native language (native vs. non-native speaker of English).

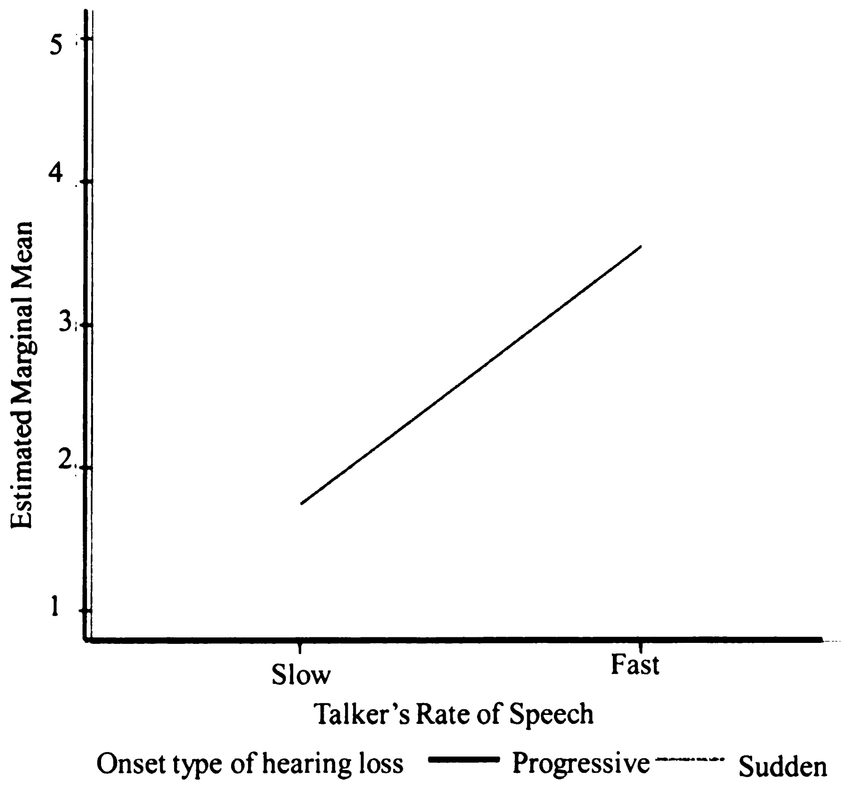

Figure 2-13. Interaction between hearing loss onset type and speaking rate.

Reduced effort in a challenging listening condition.

There were five interactions in which a subgroup showed a reduced-effort advantage for listening in a challenging condition, but little or no advantage for the corresponding favorable listening condition. All but one of these interactions was consistent with results obtained earlier in the main effects analyses of cognitive effort under "worst" listening conditions.

The unexpected interaction was between gender and background noise level. It is shown in Figure 2-14. The specifics of the interaction were that female CI users had lower cognitive effort ratings than males when listening to speech in background noise, but only at higher noise levels. The basis for this gender difference is unclear.

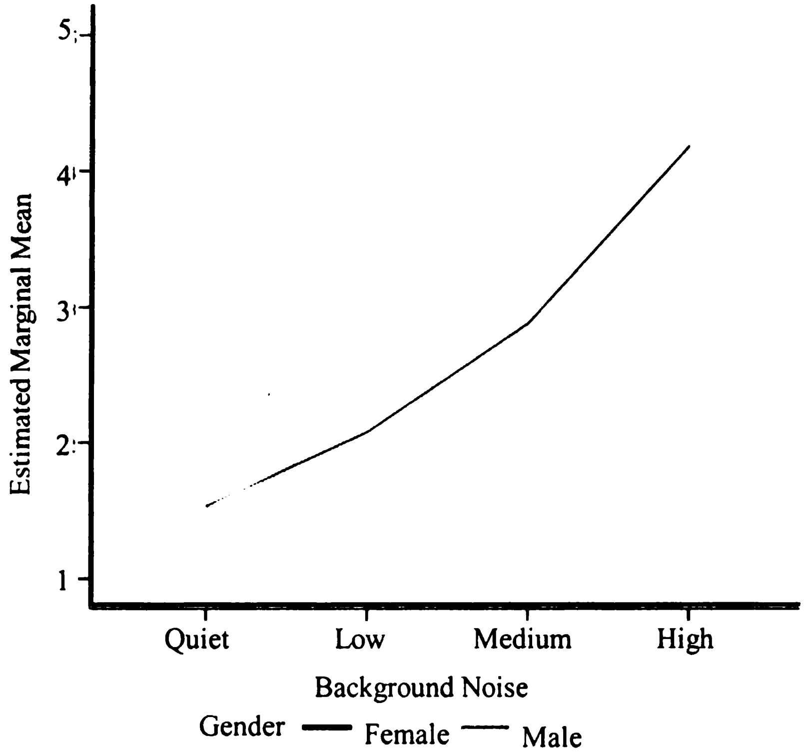

Figure 2-14. Interaction between CI users' gender and background noise level.

All of the remaining interactions in this category involved use of a hearing aid in the opposite ear, and all four were anticipated by the earlier finding that there was a significant main effect trend for this factor when respondents rated listening effort under the "worst" conditions. Here, using (or not using) a hearing aid in the opposite ear was found to interact with: (a) talker familiarity; (b) talker familiarity on the telephone; (c) rate of speech; and (d) background noise level, with those who used an opposite ear hearing aid reporting lower effort than those who did not under the most challenging of these conditions. The details of these four interactions are presented in Figures 2-15 through 2-18.

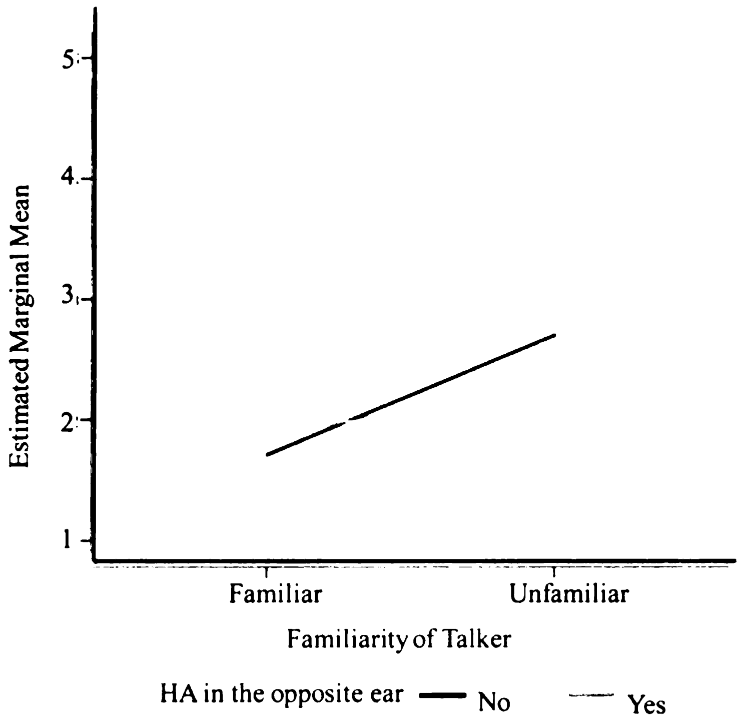

Figure 2-15. Interaction between using a hearing aid in the opposite ear and talkers' familiarity.

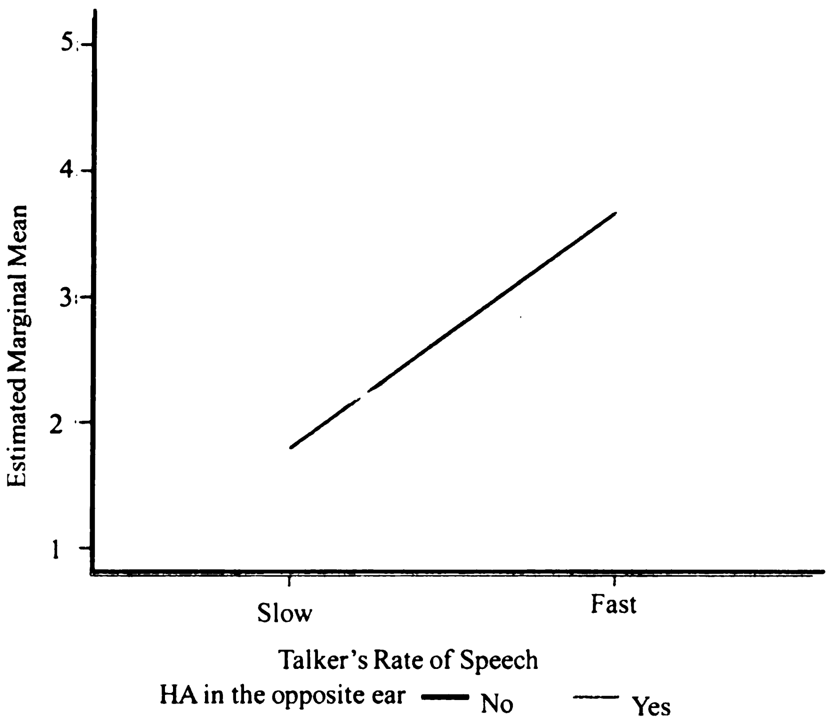

Figure 2-16. Interaction between using a hearing aid in the opposite ear and speaking rate.

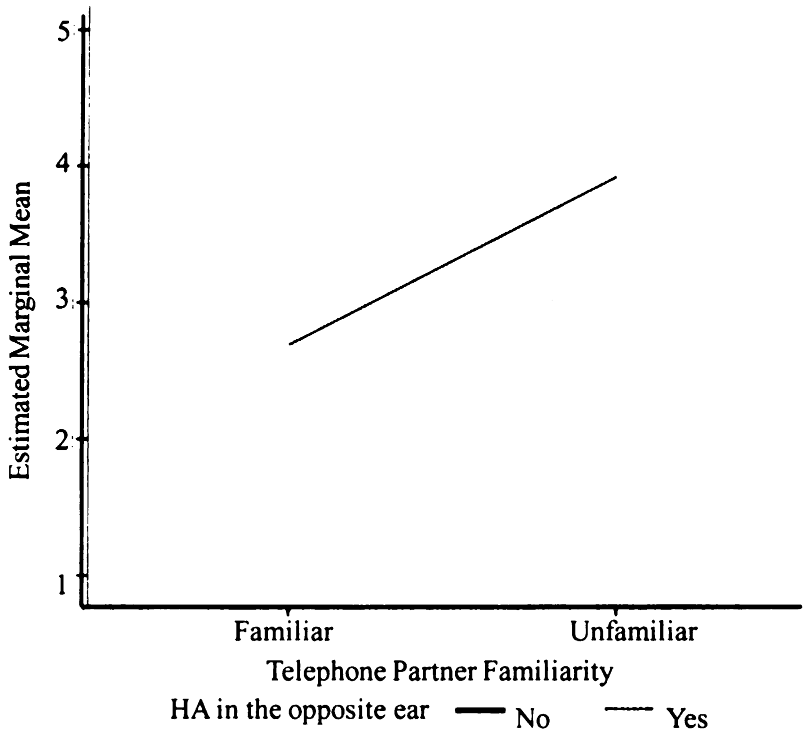

Figure 2-17. Interaction between using a hearing aid in the opposite ear and telephone partners' familiarity.

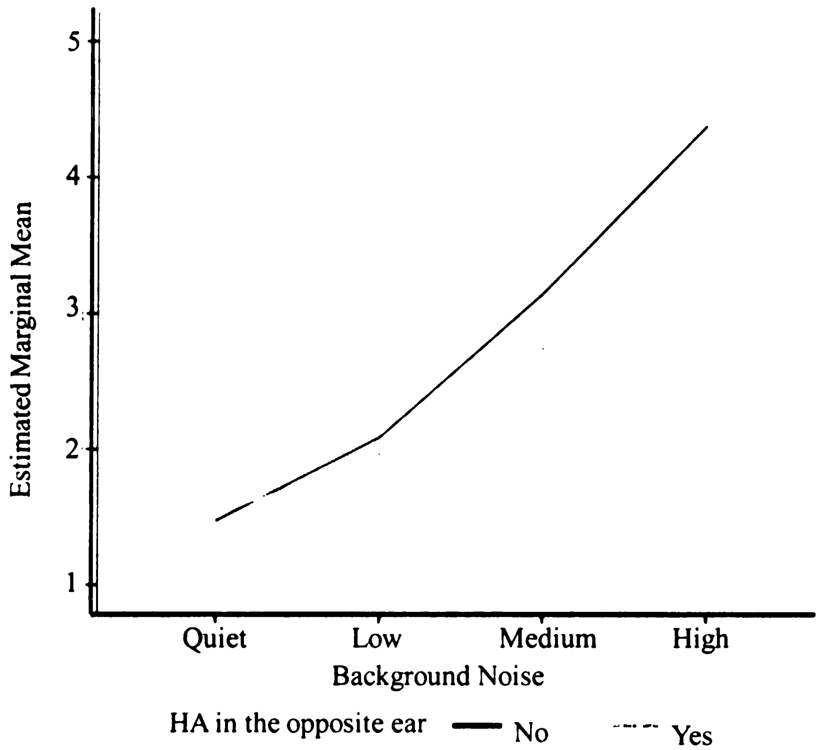

Figure 2-18. Interaction between using a hearing aid in the opposite ear and background noise level.

In summary, the present study found repeated evidence that use of a hearing aid in the opposite ear can reduce the cognitive effort needed to perceive speech under challenging listening conditions. At the same time, there was evidence that the presence of a hearing aid afforded no advantage when listening under more favorable conditions.

Age with time since implant – a cross-over interaction.

A final significant trend found here involved a crossover interaction between age and time since implant. It is shown in Figure 2-19.

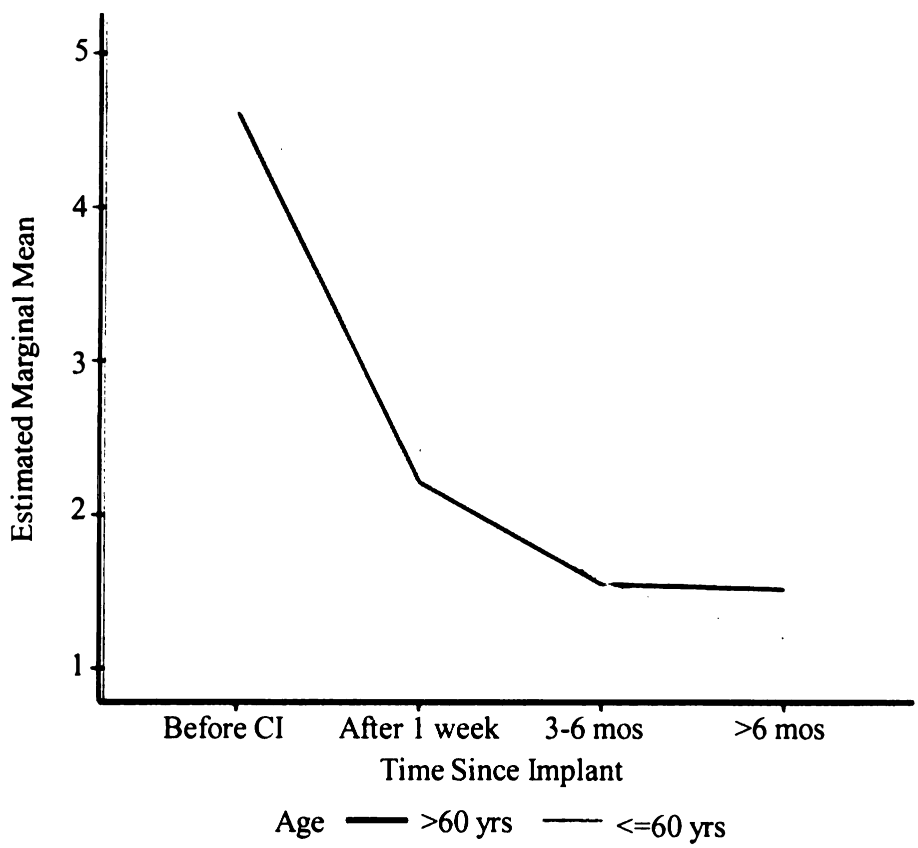

Figure 2-19. Interaction between CI users' age and time since implant.

equal after 3 months, and the younger group crossed-over to have lower ratings than the older group after 6 months. A possible explanation for this pattern may be that the older CI users exceeded the younger users in the area of listening skills at the outset, most likely because they had had a longer time to develop those skills. Better listening skills led to reduced cognitive effort in the older age group before and immediately post-implant. The younger users, on the other hand, were apparently more adept at developing new listening skills post-implant, and their development continued over at least the first 6 months, whereas skill development was largely concluded for the older group by the end of 3 months.

Conclusion

This survey found repeated evidence that post-lingually deafened CI users are aware that they must expend special cognitive effort to perceive speech. This is especially so when background noise of any kind is present, when the topic of conversation or the talker (or talkers) is unfamiliar, when the talker is a non-native speaker, and when the talker speaks rapidly.

CHAPTER 3

An Experimental Study of Cognitive Effort

Part two of this dissertation was an experimental study of the cognitive effort that must be expended by a cochlear implant user when perceiving speech. Audiometric tests of speech intelligibility are commonly used to assess the listening abilities of individuals with hearing loss and more recently of individuals with CIs. Measures of cognitive effort have been found to provide a useful complement to these audiometric tests, particularly when the goal is to compare groups and/or listening conditions that may be subtly different (Feurestein, 1992; Hick & Tharpe, 2002; McFadden, & Pittman, 2008; Rakerd, Seitz, & Whearty, 1996; Rossiter et al., 2006). The present study made an assessment of the cognitive effort needed to perceive speech when listening in quiet and under various levels of competition from background noise.

Effects of noise on speech perception by CI users, both children and adults, have been investigated in a number of previous studies (e.g., Bento et al., 2005; Dowell, Dettman, Blamey, Barker, & Clark, 2002; Most & Peled, 2007; Wolfe & Kasulis, 2008). A regular finding of these studies is that background noise presents particular challenges for CI users, far more so than for normally-hearing listeners (see Chapter 1, Level of Background Noise for a review). The present experimental study asked a complementary question: How do the challenges of listening in noise affect a CI user's ability to *multi-task* speech perception with other activities? As an example, consider someone who must take notes in a classroom setting while listening to a lecture. Then imagine that noise arises in the background, due to events going on either inside or outside of the lecture

hall. Additional demands on any listener's cognitive resources are likely to result (Paccia-Fuller, 2003a). However, given the special difficulties that CI users can have with noise, it is quite possible that these added demands will be significantly greater for them than for normally-hearing listeners in this same situation. That possibility was directly tested in this study.

Dual-task Testing

One method for measuring the cognitive resources that someone must commit to complete any task is to have that task be carried out simultaneous with a second task. There is good evidence that an individual has limited cognitive resources to allocate to these dual-tasks (e.g., Kahneman, 1973; Baddeley, 1986; Carpenter, Miyaki, & Just, 1994). Consequently, when one of them demands increased resources, fewer are left for the other task. In studies like the present one, the cognitive demands of one task are of primary interest (the demands of speech perception are of primary interest here), and performance of the second task then becomes a source of information about those demands. Specifically, reduced performance on the second task provides evidence of increased cognitive resource commitments to the primary task.

Rakerd, Seitz, and Whearty (1996) used this paradigm to compare the cognitive effort needed by hearing impaired listeners to that of normally-hearing listeners when both groups were attending carefully to spoken messages. Their primary task was a speech comprehension task in which subjects were required to listen for understanding to minute-long spoken passages. The secondary task was a memory task in which subjects learned and later recalled strings of digits. The index of cognitive effort for the speech

task was the number of digits that were forgotten. Results showed that the hearing impaired listeners allocated significantly more cognitive resources to speech comprehension than did a comparison group of normally-hearing listeners. Test protocols similar to those used by Rakerd et al. (1996) were employed in the present study of postlingually-deafened adults who use CIs.

Here, a group of CI participants and a comparison group of normally-hearing participants were engaged in a dual-task activity that required that they: (a) listen carefully to sentence-long speech samples, and (b) simultaneously perform a visual reaction time task that indexed the difficulty of speech listening. The speech listening task was performed in quiet and in several different levels of competing background noise.

Methods

Participants

There were two groups of participants, one who were cochlear implant users (group CI) and a second group who had normal hearing (group NH).

The cochlear implant users group.

Twelve postlingually-deafened adults comprised the CI group. All participants were recruited from the University of Michigan CI Program. There were 8 females and 4 males. Their ages ranged between 23–82 years old (mean=51.8) and they were all native

speakers of American English. Table 3-1 provides information about the etiology of hearing loss for each CI participant, and about other aspects of their hearing history.

Table 3-1. *Demographics and hearing history of the individuals in the CI group.*

Participant	Etiology	Age	Age when HL identified	Age when HL became profound	Type HL
1	Hereditary	47	5	42	Progressive
2	Hereditary	40	2.5	2.5	Sudden
3	Ushers syndrome	50	6	45	Progressive
4	Unknown	51	5	20	Progressive
5	Meningitis	31	5	12	Progressive
6	Unknown	55	22	53	Progressive
7	*Toxic* drugs	82	20	20	Progressive
8	Otosclerosis	72	30	40	Progressive
9	Noise	51	39	44	Progressive
10	Hereditary	23	5	16	Progressive
11	Hereditary	59	30	Unknown	Progressive
12	Unknown	56	57	17	Sudden

Inclusion criteria.

To be eligible for participation in this study, a CI user had to be a postlingually-deafened adult who used a unilateral multichannel CI with full electrode insertion, and who had been using the device for 12 months or longer. It has been reported that the most dynamic enhancements of speech perception usually takes place in the first 12 months after fitting of a CI (Hamzavi, Baumgartner, Pok, Franz, & Gstoettner, 2003). A similar conclusion was reached in the survey study reported above (see Chapter 2).

Another inclusion criterion for this study was that the CI user must have scored over 80% correct on the open-set sentence recognition "Hearing in Noise Test" (Nilsson, Soli, & Sullivan, 1994). This threshold was selected because it has been reported that late-deafened adults with a unilateral CI can often achieve such a score on sentence recognition tests (Mok, Grayden, Dowel, & Lawrence, 2006).

The last condition for participating was that the duration of deafness prior to receiving a CI was 60% or less of the participant's life. Adults implanted at a younger age and with smaller percentages of life in deafness have been found to achieve the highest levels of short-term postoperative speech recognition success (Blamey et al., 1996; Green, Julyan, Hastings, & Ramsden, 2005; Oh et al., 2003).

The normally-hearing (NH) group.

The NH group consisted of 18 individuals. Participants were 21 to 59 years old (mean = 36.16). There were 8 females and 10 males. They were either members of the Michigan State University community or were acquaintances of the CI participants. All NH participants passed a hearing screening test, with criteria as follows: binaural hearing thresholds of 25 dB HL or better at 1000, 2000, and 4000 Hz.

Recruitment procedures.

An information letter was mailed to possible participants explaining the study's purpose, the confidentiality with which the study would be conducted, the absence of any known risk factors, and the financial compensation for participants ($35). Interested individuals from the NH and CI groups then contacted the study investigator to schedule an appointment to be tested. Participants were given the choice to be tested in one of two locations, either at the University of Michigan Cochlear Implant Program site or at Michigan State University's Department of Communicative Sciences and Disorders.

The Dual-task

The participants performed two tasks during the experiment, a speech perception task that is described in the next section, and a visual reaction time task that is described in the immediately following section. As noted above, the cognitive demands of perceiving speech were of primary interest in this study, and those demands were assessed by means of their impact on a participant's visual reaction time when the two tasks were in dual-task competition.

The speech perception task.

Stimuli.

The stimuli for the speech perception task were sentences drawn from the BKB speech recognition test set (Bench, Kowal, & Bamford, 1979). These stimuli were presented to a listener in quiet, and in different levels of background noise. In all cases, the background noise type was multi-talker "speech babble" (14 talkers). Multi-talker babble was selected because of its effectiveness as a masker of speech (Carhart, Tillman, & Greetis, 1969; Lewis, Benignus, Muller, Mallott, & Barton,, 1988).

The full BKB speech test set is made up of 21 lists, each having 16 sentences and 50 keywords (3 or 4 per sentence). The sentences were compiled originally from the utterances of children with hearing loss and contain straightforward vocabulary and syntax. Although designed for testing children, these sentences have also proved useful and appropriate in testing adults (Cainer, James, & Rajan, 2008; Holden, Skinner, Holden, & Binzer, 1995).

For the current study, a subset of the BKB test sentences was recorded by an adult make talker with a General American dialect. The sentences were spoken in a quiet environment, and digitized at the time of original recording (PCM 16-bit recording, sample rate = 22,050 Hz). Digital audio editing software (GoldWave V5.2) was then used to equalize the levels of the individual sentences, and to organize them into stimulus lists with a separation of approximately two seconds between the succeeding sentences in a list. An individual BKB sentence could appear in one list only. Five different stimulus test lists of 32 sentences each were created for the experiment. For each listener, these lists were randomly assigned to the single-task and dual-task test conditions as needed (see below), with the constraint that a list was never repeated. A practice list of 16 sentences (different from any of the test lists) was also created (See Appendix B for a complete listing of test lists and practice list).

Procedure.

Participants were tested individually, while sitting quietly in a sound-attenuated booth. Stimuli (speech + noise) were presented from a loudspeaker directly in front of and one meter away from the participant. The task was to attend carefully to each sentence that was presented and to repeat the sentence back immediately upon its completion. A directional microphone and a digital audio recorder (Zoom H4 Digital Recorder) captured the listener's responses. Those responses were later scored for accuracy of reporting of the BKB key words. For each condition, the participant completed 32 trials (one test list).

The CI users were tested while wearing their CIs. One user who also wore a hearing aid in the opposite ear was asked to take the aid off because the current study aimed at assessing performance of CI users using a unilateral cochlear implant. The binaural benefit and additive speech information obtained from using a hearing aid in conjunction with a CI was not investigated.

Visual reaction time task.

For the visual reaction time (RT) task, a visual stimulus (a graphic image "X" that filled approximately two thirds of the display) was presented at random intervals on a computer screen. The participant was instructed to monitor continuously for this symbol and to press a response button immediately whenever it appeared. The computer screen was in clear view, directly in front of the participant and one meter away.

The RT task was performed singly to obtain a baseline estimate of a participant's reaction time, and also in dual-task competition with the speech task. In both instances, there were a total of 24 test trials. The reaction time for a trial was calculated from the moment of stimulus onset to the moment of the participant's response (a button press). If there was no response within 1500 milliseconds, a trial was scored as a "miss" and the trial was dropped. The maximum number of misses made in any condition by any listener was 3. The average number of misses was 1. The reaction time for a trial was rejected as "impossibly fast" if it was less than 150 milliseconds. Rejections of this kind were rare (28 total for the two participant groups combined). The reaction time for a condition was calculated as the average of the RT's obtained on all of the valid trials.

Visual stimulus presentation.

As noted, there were 24 RT test trials per condition. For the dual-task test conditions, the visual stimuli were presented in coordination with the presentation of the

BKB sentences. A maximum of one stimulus presentation could occur during any one sentence, and it did so on the following schedule. The visual symbol was either not presented at all (8 trials, 25% of all sentences) or it was presented with equal probability (8 trials each) during the first third, middle third, or final third of a sentence. For the single-task reaction time test the visual stimuli were presented on the same time schedule as for a dual-task test. (They were in fact coordinated with one of the speech test lists, with the sound turned off.)

The testing procedures

All testing, both single-task and dual-task was completed during a single test visit that lasted approximately 90 minutes. The sequence of events for the visit is described in this section.

Informed Consent.

A participant consent form was reviewed and signed at the start of the visit. Any questions regarding the consent were fully addressed prior to signing. The consent form was approved by the Institutional Review Boards of the University of Michigan and Michigan State University.

Hearing Screening or survey completion.

Normally hearing participants were given a hearing screening (details provided above) at the conclusion of the signing of the consent form and prior to their participation in the main experiment.

Cochlear implant participants completed a survey regarding their self-perceptions of the cognitive effort needed to perceive speech. This was the same survey that was reported on in Chapter 2 above.

Familiarization with the Stimuli.

Next, participants were familiarized with the audio and visual stimuli that were to be used in the experiment. Sixteen BKB sentences, four at each of four different signal-to-noise ratios covering the range of those to be heard during testing, were presented as examples. Also, four visual stimuli were presented.

Practice trials.

The participant next completed a series of eight single-task practice trials (four speech trials and four visual RT trials) and eight dual-task practice trials. Any questions about the procedures were fully addressed at this time.

Tests

Single-task tests.

The single-task tests were completed next. First, a participant completed one 32-trial speech test. Then, the participant completed a 24-trial visual reaction time test.

Dual-task tests.

Favorable listening conditions.

Next, dual-task testing was conducted for all participants (both NH and CI) under the two most favorable listening conditions: (1) speech presented in quiet, and (2) speech presented at a signal-to-noise ratio (S/N) of +15 dB. All of the participants from both groups were able to successfully complete dual-task testing under these two most favorable listening condition tests.

The test in quiet was conducted first. Then, after a break (approximately 5 minutes), the test at +15 dB was conducted. With one exception (a dual-task test of several CI participants conducted at S/N=+10 dB) (see below), dual-task testing was sequenced to progress from the least challenging condition (speech in quiet) through progressively more challenging conditions (decreasing S/N) to accommodate the needs of CI participants in particular. NH participants were tested in this same sequence for comparison.

Dual-task test at S/N = +5 dB.

All of the CI participants and 14 of the NH participants were next tested at the more challenging S/N of +5 dB. Every NH participant was able to perform the dual tasks at this S/N. However, this condition proved more challenging for most of the CI participants. A number of them had difficulty accurately identifying the speech, and in one instance a participant asked that the test be terminated.

Additional dual-task tests.

CI participants testing at S/N = +10 dB. Following the completion of the S/N = +5 dB test, several of the CI participants were given a dual-task test in which the noise level was reduced by 5 dB (i.e, S/N was set at +10 dB). This was done to reduce the challenge of speech listening somewhat, possibly to a point where accurate speech perception could be maintained under dual-task conditions by CI users. Six of the twelve CI participants were tested in this way.

NH participants testing at S/N =0 dB. Following their completion of the S/N = +5 dB test, all 14 of the NH participants were tested at a more challenging S/N level to assess the possible consequences for their dual-task performance. Specifically, they were tested at S/N = 0 dB.

Results and Discussion

As noted above, participants in the present study were engaged in two tasks, a speech perception task that was of primary interest here, and a visual reaction time task that provided information about the cognitive demands of speech perception. For the speech task, a participant attended to and repeated back sentence-long speech stimuli (Bench, Kowal, & Bamford, 1979). For the visual reaction time task, the participant responded as quickly as possible (with a button press) to a visual stimulus that randomly appeared on a computer screen. These tasks were performed both separately (single-task testing) and simultaneously (dual-task testing). The speech task was performed in quiet and when listening against several different levels of background noise.

Raw Scores and Normalized Scores

Data of two types are presented below. The first type are *raw scores*. For the speech task, the raw scores for a participant were the percentages of keywords correctly identified in the single-task test and in the dual-task tests conducted at various signal-to-noise ratios. For the reaction time task, the raw scores were the participant's mean reaction times for the single-task test and for the dual-task task tests.

The second type of data considered here are *normalized scores*. Normalized scores were calculated for the various dual-task test conditions based on a participant's performance on the corresponding single-task test. For the speech task, the normalized score was a *proportion* calculated by dividing the dual-task percent-correct score for a condition by the single-task percent-correct score. For the reaction time task, the normalized score was a *difference*, calculated by subtracting the single-task reaction time from the corresponding dual-task reaction times. Raw scores and normalized scores were both statistically compared across conditions by analysis of variance and, as called for, by t-tests.

Favorable Listening Conditions

This section presents the raw score and normalized score results obtained for all tests (both single-task and dual-task) that were conducted under favorable listening conditions. Every participant was tested under these conditions. Results are presented first for the NH group and then for the CI group.

Normally-hearing listener group.

Speech perception test results.

Raw scores. Figure 3-1a shows the NH listeners' raw-score speech perception test results (means and standard errors) for three tests. Test one was the single-task speech perception test that was conducted in quiet. This test is identified in Figure 3-1a and in a series of subsequent figures as ST:Sp. Tests two and three were dual-task tests conducted under favorable listening conditions. For one of these tests; there was no background noise; i.e., the speech was presented in quiet (condition DT:Q). For the other test the S/N was set at +15 dB (DT:+15).

Consistent with the description of these as favorable listening conditions, the NH listeners had mean scores of greater than 99% correct for all three of these tests. Accordingly, an ANOVA found no significant difference among these conditions ($F(1, 17) = 1$; $p < 0.33$).

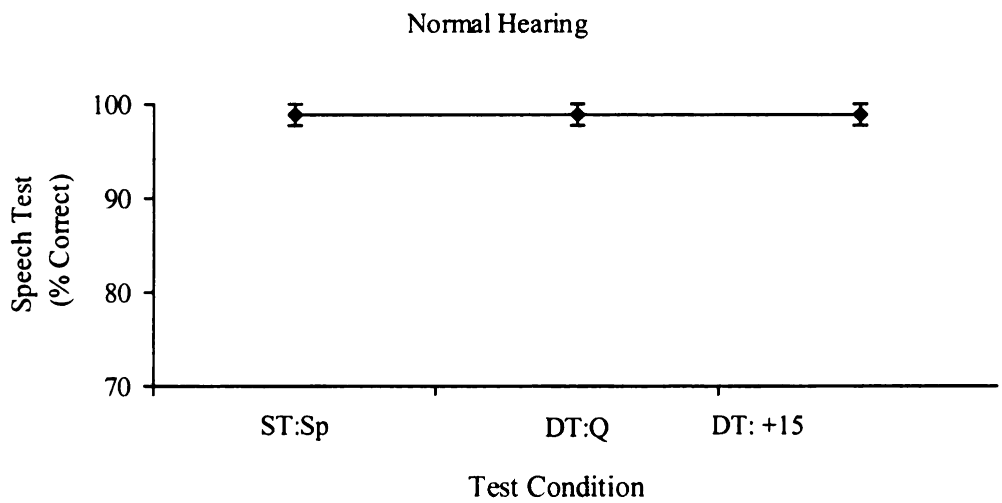

Figure 3-1a. NH listeners' (n=18) raw score results for the speech test (mean +/-1 SE) performed as a single-task (ST:Sp) and in dual-task in competition with speech in quiet (DT:Q) and speech presented at +15 dB S/N (DT:+15).

Normalized scores. For the dual-task conditions, a data transformation was carried out to derive normalized speech perception test scores from the raw scores. Specifically, each dual-task raw score was divided by the raw score for the single-task speech test (ST:Sp) to calculate a proportion score. A proportion score less than 1.0 would indicate that some speech information was lost to a participant in a dual-task test relative to the single-task baseline. This could be due to the added background noise present in most of the dual-task test conditions (but not in condition DT:Q) or possibly due to the added cognitive complexity of the dual-task test situation itself.

Figure 3-1b shows the NH listeners' normalized scores for the two favorable listening dual task tests. The means for both tests were very close to 1.0 (DT:Q mean = 1.00; DT:+15 mean = 0.98). Also, the means were not significantly different from one another ($t(17) = 1.0$; $p < 0.33$), indicating that for NH participants, speech perception at

S/N=+15 dB was approximately equivalent to speech perception in quiet. This finding was expected, based on a number of prior studies of speech perception by normally-hearing adults (e.g. Crum & Matkin, 1976; Tillman, Carhart, & Olsen, 1970).

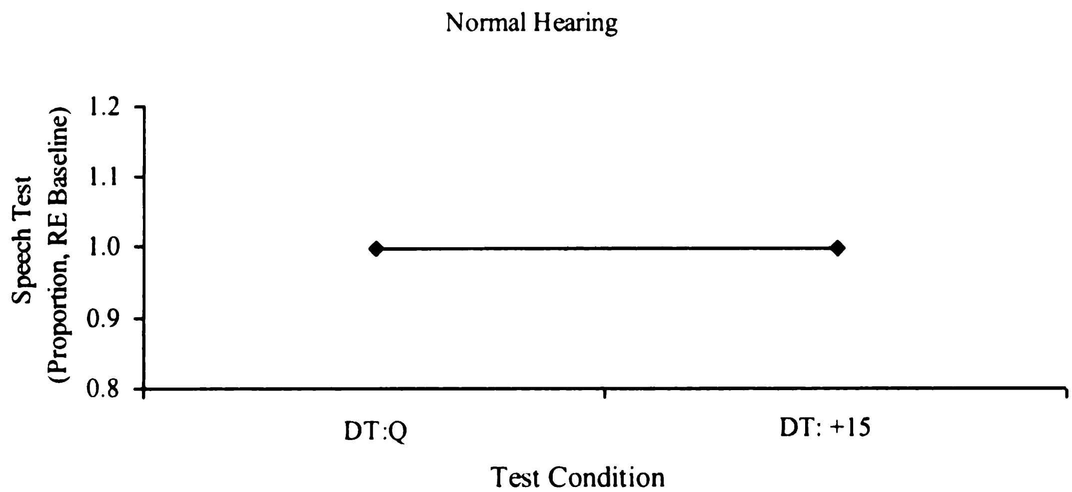

Figure 3-1b. NH listeners' normalized score results for the speech test.

Reaction time test results.

Raw scores. The visual reaction time task was the secondary task in the experiment. The instruction for this task was to respond as quickly as possible (with a button press) to a randomly appearing visual probe stimulus. Participants were also instructed to pay equal attention to this task and the speech task in instances where the two tasks were in dual-task competition.

Figure 3-2a shows the NH participants' mean reaction times (+/- 1 standard error) for three test conditions: (1) single-task visual reaction time testing (labeled ST:RT); (2) dual-task testing coincident with speech perception when the speech was presented in quiet (DT:Q); and (3) dual-task testing when speech was presented at S/N=+15 dB (DT:15dB).

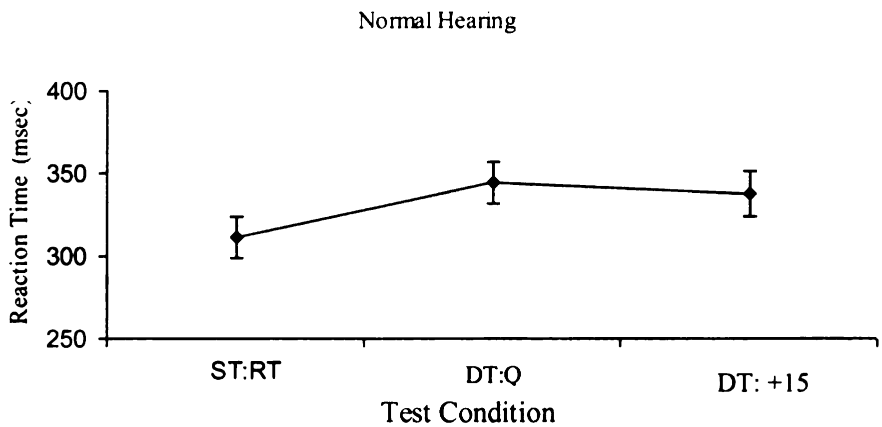

Figure 3-2a. NH listeners' (n=18) raw score results for the visual reaction time test (mean +/-1 SE) performed as a single-task (ST:Sp) and in dual-task in competition with speech in quiet (DT:Q) and speech presented at +15 dB S/N (DT:+15)

A statistical analysis of the raw scores shown in Figure 3-2a found a significant difference among the three conditions overall ($F\ (1.31, 22.29) = 5.458$, $p < 0.009$). It can be seen that the NH participants reacted somewhat faster in the single-task test than in either of the dual-task tests. Post-hoc tests, presented in Table 3-2 below, indicated that there was a significant difference between the single-task score and each of the dual-task scores, presumably because the dual-task imposed greater cognitive demands. There was no significant difference between the two dual-task scores, indicating that the NH participants found listening to speech at S/N=+15 dB to be no more cognitively effortful than listening in quiet.

Table 3-2. *Visual reaction time score for the NH group. Post-hoc comparisons.*

Test condition	Mean Difference	Std. Error	t	Significance
ST: Q- DT: Q	-32.7	12.25	-2.670	0.02
ST: Q – DT: +15	-26.2	12.23	-2.145	0.05
DT: Q – DT: +15	6.5	5.50	1.180	0.25

Normalized scores. The raw RT scores for the two dual-task tests were converted to normalized difference scores (DT raw score - ST:RT raw score) to show any reaction time slowing that may have resulted from added cognitive load in a dual-task test. Figure 3-2b shows the results. There was some modest slowing relative to baseline for both dual-task tests. Specifically, the mean normalized score for listening in quiet was +32.7 msec, and for listening at S/N=+15 dB it was +26.2 msec. The latter RT score may have been slightly smaller because the DT:15 test was performed after the DT:Q test by all participants. Seemingly, they were more practiced. The statistical difference between the two means was not statistically different (p>0.25)

Overall, these normalized scores and the raw scores discussed above indicate that: (a) NH listeners experienced at most a minimal cognitive load when perceiving speech under these favorable listening conditions; and (b) for them, the load was no greater when listening at S/N=+15 dB than when listening in quiet.

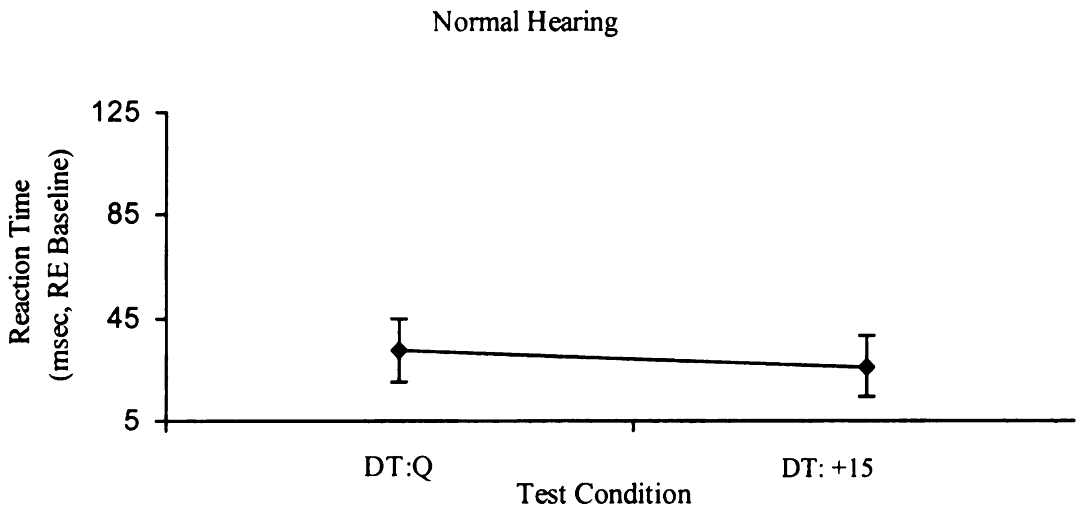

Figure 3-2b. NH listeners' raw score results for the visual reaction time test.

Cochlear implant listeners.

Favorable listening condition results for the CI users are presented in this section. Their speech perception testing results are considered first, then the visual reaction time results assessing the cognitive effort required for speech listening are presented.

Speech perception test results.

Raw scores. Figure 3-3a shows the CI participants' raw speech perception scores. They scored better than 80% correct for all three tests, and better than 90% correct for the DT:Q test. This is consistent with reports that CI users can achieve high levels of speech perception accuracy when listening at favorable signal-to-noise ratios.

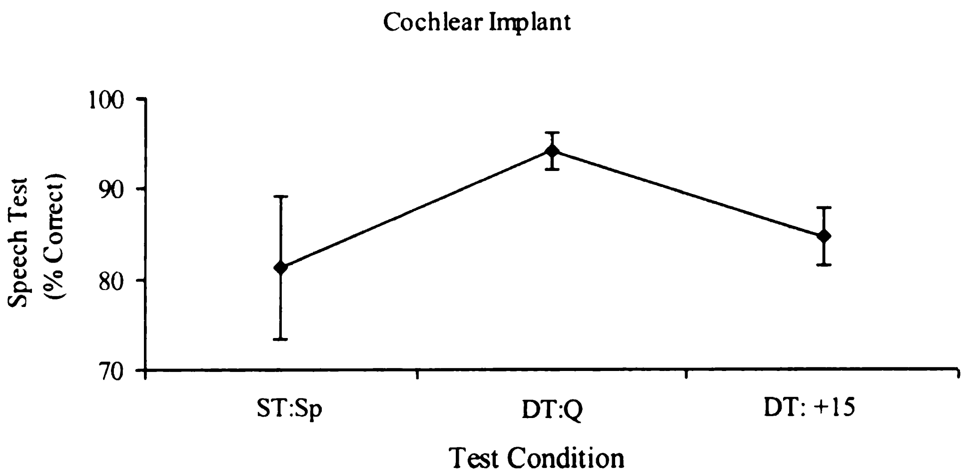

Figure 3-3a. CI users' (n=12) raw score results for the speech test.

A statistical analysis of the results shown in Figure 3-3a found a marginally significant overall difference among the means (F (1.53, 16.85) = 4.18, $p<0.04$). Post-hoc testing indicated that there was a significant pairwise difference between the means for the two dual-task test conditions ($t(11) = 3.20$, $p<0.008$). Specifically, the scores for the CI users S/N=+15 dB condition were significantly lower than their scores for the speech in quiet condition. Apparently, for CI users, even the low level of background noise present at S/N=+15 was sufficient to produce a measurable reduction in speech perception performance in the experiment.

Normalized scores. The normalized score results for the CI participants are shown in Figure 3-3b. An unexpected finding regarding these speech perception tests was that, as a group, the CI participants scored somewhat higher for the two dual-task tests than for the single-task test. Accordingly, the normalized ratios shown in Figure 3-3b are greater than 1.0. The most likely explanation for this finding is that dual-task testing came later in the test session than single-task testing, which meant that the CI users' speech perception performance could have been aided by familiarity and practice effects. Certainly the normalized scores show that the CI users were able to maintain good accuracy in their speech perception, even when dealing with the complexities of dual-task testing.

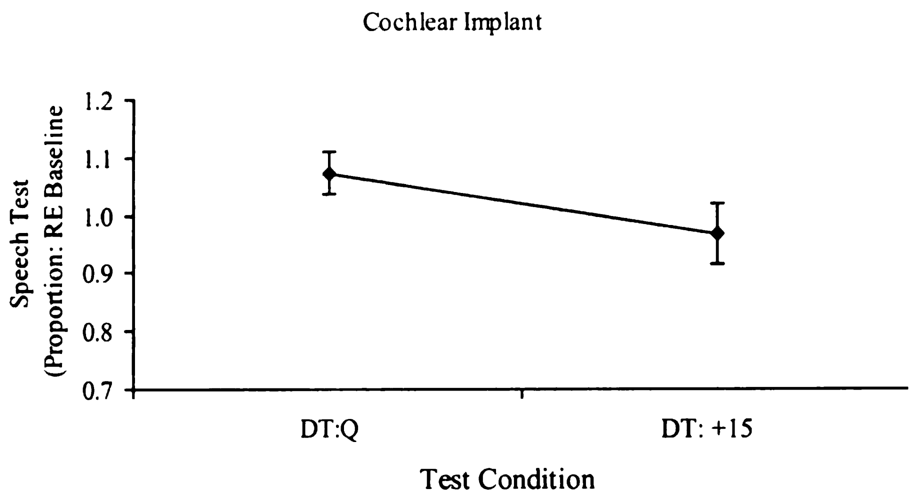

Figure 3-3b. CI users' normalized score results for the speech test.

There was a statistically significant difference between the normalized scores for listening in quiet (DT:Q) and listening at S/N=+15 dB (DT:+15), with performance lower for the +15 dB condition. This again indicates that unlike the NH listeners, CI users experienced some measureable difficulty in performing the speech task in background noise, even at this low noise level.

Comparisons to the NH listeners. Finally, Table 3-3 directly compares the CI listeners' mean scores with the NH listeners' mean scores for all of the speech perception tests described in this section. While the scores for the CI group tended to be lower than those for the normally hearing group, and were, in fact, statistically significantly lower in two instances, it is clear that that the CI users were able to maintain substantial accuracy in their speech perception for all tests conducted here under favorable listening conditions. The principal question addressed in this dissertation is how much effort the CI users had to expend to achieve this perceptual success. The extent of that effort is indexed by their performance on the visual reaction time task, as reported in the next section.

Table 3-3. *Comparisons of the CI and NH listener group means on several measures of speech perception performance. (Significance indicators: * p<0.05, **p<0.01, ***p<0.001).*

Score/ Condition	CI Group	NH Group	Difference (CI-NH)	t-test	adj df	p-value	Signif.
Raw Scores (% Correct)							
ST:Sp	88.9	98.9	-10.0	-2.624	13	0.021	*
DT:Q	94.2	98.9	-4.7	-2.062	18	0.054	
DT:+15	84.2	98.8	-14.6	-4.135	14	0.001	***
Normalized Scores (ratio)							
DT:Q	1.07	1.00	0.07	1.999	11	0.071	
DT:+15	0.97	0.99	-0.02	-0.638	11	0.537	

Visual reaction time results.

Raw scores. Figure 3-4a presents the visual reaction time raw scores for the CI user group. There was a highly significant overall difference among the means ($F(1.61, 17.67) = 36.68$, $P<0.0001$).

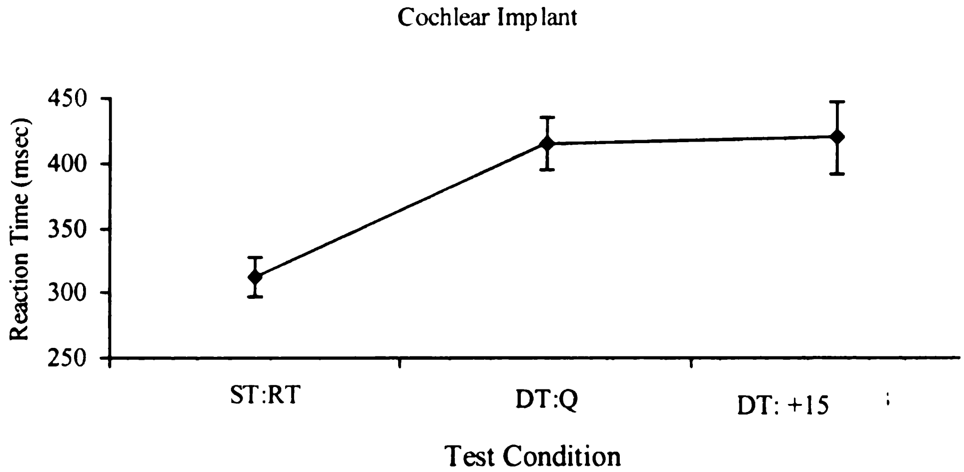

Figure 3-4a. CI users' raw score results for the visual reaction time test.

Post-hoc testing (see Table 3-4) found that there was a significant difference between the single-task mean and each of the dual-task means (p<0.001 in both cases). Specifically, the CI users were significantly slowed on average relative to the single-task baseline when reacting under both dual-task test conditions. The extent of this slowing is shown in the normalized test scores presented in Figure 3-4b and discussed below.

Table 3-4. *Visual reaction time scores for the CI group. Post-hoc comparisons.*

Test condition	Mean Difference	Std. Error	t	Significance
ST: Q- DT: Q	-102.8	11.98	-8.58	0.001
ST: Q – DT: +15	-107.2	17.28	-6.19	0.001
DT: Q – DT: +15	-4.4	12.60	-0.35	0.731

Normalized Scores. Figure 3-4b presents the CI users' normalized scores for the dual-task tests conducted with speech in quiet and at S/N = +15 dB. For both of these conditions there was notable slowing of performance relative to the single-task baseline. Specifically, the CI users were slowed on average by 102.8 msec when listening in quiet, and by 107.2 msec when listening at S/N=+15 dB. By contrast, the NH control group has normalized mean scores of just 32.7 msec and 27.2 msec for these two conditions.

The clear implication of these results is that the cognitive effort required to achieve accurate speech perception was substantial for the CI users, so substantial that it appreciably slowed their ability to perform the competing visual reaction time task.

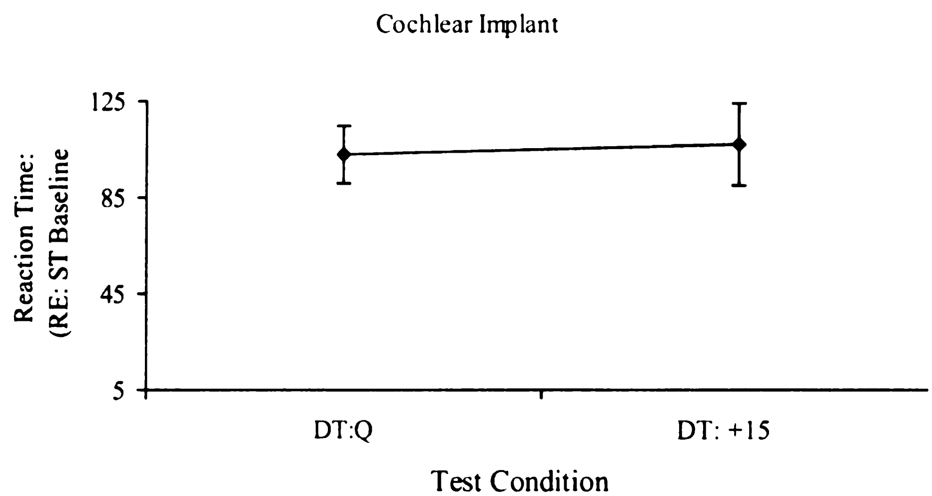

Figure 3-4b. CI users' normalized score results for the visual reaction time test.

Comparisons to the NH listeners. Table 3-5 directly compares the CI listeners' mean scores with the NH listeners' mean scores for all of the reaction time tests described in this section. There were several notable findings. The first is that the two groups had nearly identical mean raw scores for the single-task reaction time test (difference=0.8 ms). Hence they were well matched at baseline. By contrast, the two groups had significantly different raw scores for both dual-task tests. The CI group was slower than the NH group by 70.8 msec on average when listening to speech in quiet, and by 81.8 msec when listening to speech at S/N = +15 dB. This provides strong evidence that the cognitive effort required to perceive speech was substantially greater for the CI group. Finally, the statistical differences between the two groups were especially strong with respect to their normalized scores ($p<0.001$ in both cases).

Taken together, the results of this experiment provide strong evidence that CI users must make a significantly greater than normal commitment of cognitive effort in order to perceive speech, even when listening under acoustical conditions that are favorable.

Table 3-5. *Comparisons of the CI and NH listener group means on several measures of visual reaction time performance. (Significance indicators: * $p<0.05$, ** $p<0.01$, *** $p<0.001$).*

Score/ Condition	CI Group	NH Group	Difference (CI-NH)	t-test	adj df	p-value	Signif.
Raw Scores (msec)							
ST:Sp	312.11	311.31	0.8	0.041	23	0.967	
DT:Q	414.86	344.03	70.8	2.961	19	0.008	**
DT:+15	419.31	337.53	81.8	2.627	16	0.018	*
Normalized Scores (msec)							
DT:Q	102.75	32.72	70.03	4.087	23	<0.001	***
DT:+15	107.20	26.22	80.98	3.821	21	<0.001	***

More Challenging Listening: Dual-Task Test at S/N = +5 dB

This section presents the results of the dual-task test that was conducted at S/N=+5 dB. This listening condition was substantially more challenging than the two previous conditions (listening in quiet, listening at S/N = +15). Speech perception scores for a number of the CI participants fell significantly in this condition. The test was terminated at the request of one CI participant. It was carried through to completion by the other 11 CI participants, and their results are presented below. Also presented are results for a comparison group of n=14 NH listeners who were tested at S/N=+5 dB. All of the NH participants were able to complete this test.

Normally-hearing and CI listeners.

Speech perception testing.

Raw scores. Figure 3-5a gives the speech test raw scores for participants in the NH group and for participants in the CI group. There is a plot of each individual participant's score, and also a plot of the mean score for each group.

The NH listeners were able to maintain a high level of speech perception accuracy when listening at S/N=+5 dB, with all but one of them scoring 98% correct or above. By contrast, the CI users differed widely in their speech perception accuracy. One scored at a level matching that of the CI participants, but for the majority of the CI users listening at S/N=+5 dB posed considerable difficulty. The mean score for the CI group was 38% correct, which was significantly below the NH participants' mean (t (23) =7.73; p<0.0001).

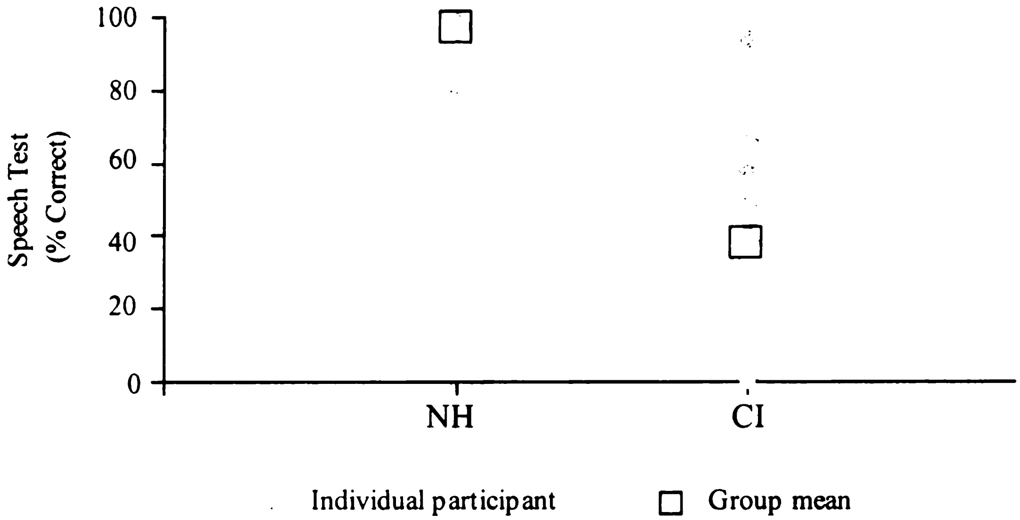

Figure 3-5a. Speech test raw scores for the dual-task test at S/N=+5 dB. Scores are plotted separately for each participant in the NH group (n=14) and in the CI group (n=11). The mean score for each group is also presented.

Normalized scores. Figure 3-5b shows the normalized scores for the S/N = +5dB dual-task test. The mean for the NH group was very close to 1.0 (mean = 0.98) compared to the CI group mean of just 0.43. Generally, all participants in the NH group performed far better than the CI participants. Only two of the CI users (18%) had normalized scores in the range of the scores for NH participants.

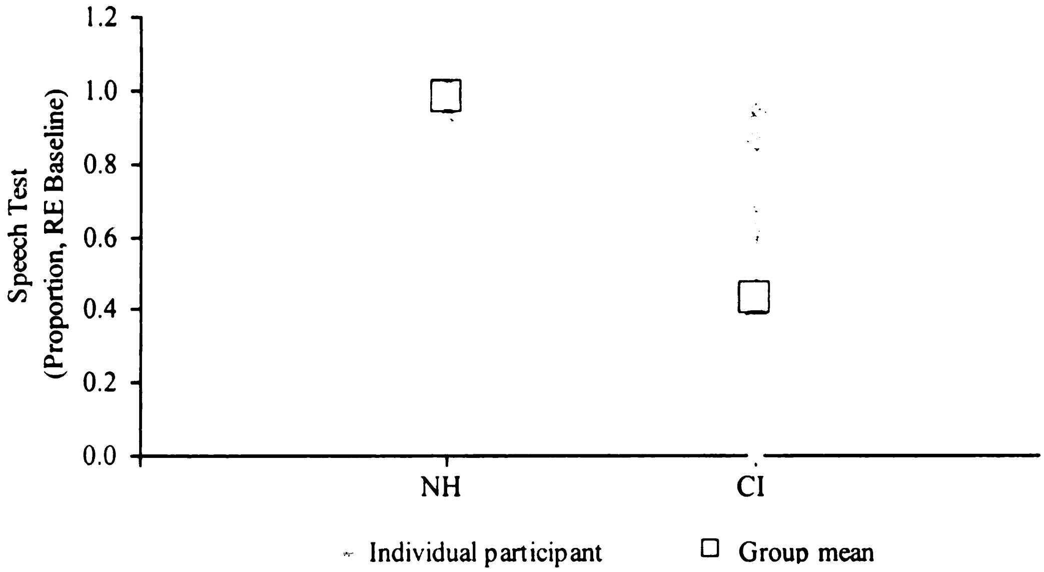

Figure 3-5b. Speech test normalized scores for participants in both groups when tested at +5dB S/N.

A *t-test* on the results presented in Figure 3-5b indicated that there was a highly significant difference in performance between the groups (t (24) =6.83; $p<0.0001$). It is clear that background noise at this level, specifically +5dB S/N, posed great difficulty for CI users' speech perception. The next section shows the consequences of this difficult listening for cognitive effort and, in turn, for performance on the visual reaction time task.

Visual reaction time testing.

Raw scores. Raw score results for the visual reaction time test at S/N = +5 dB are presented in Figure 3-6a. It can be seen that the NH listeners were faster on average (mean= 363.5 msec) in their visual reaction times than the CI users (mean= 445.9 msec). But it can also be seen that there was some variability in the reaction times for both groups, and considerable overlap in the individual scores. Statistical analysis of the raw

scores indicated a statistically significant difference between the two groups at S/N=+5dB (t (23) =-2.442; *p*<.035).

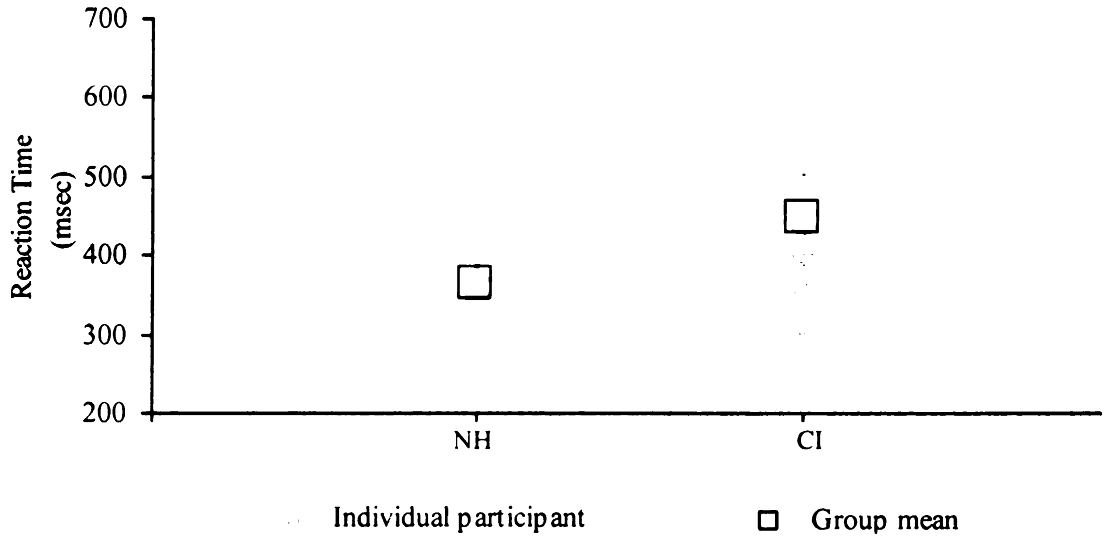

Figure 3-6a. Visual reaction time raw scores in both groups when tested at +5dB S/N.

Normalized scores. Normalized scores, presented in Figure 3-6b below, show a substantially longer visual reaction time (relative to the single-task baseline) for the CI group (mean=136.8 msec) than for the NH group (mean= 49.83 msec). This difference was statistically significantly (t (23) =-3.506, *p*<.002). The slowed responses of the CI group in this condition provide evidence of increased cognitive resource commitments to the primary task when listening to speech in this unfavorable acoustical condition.

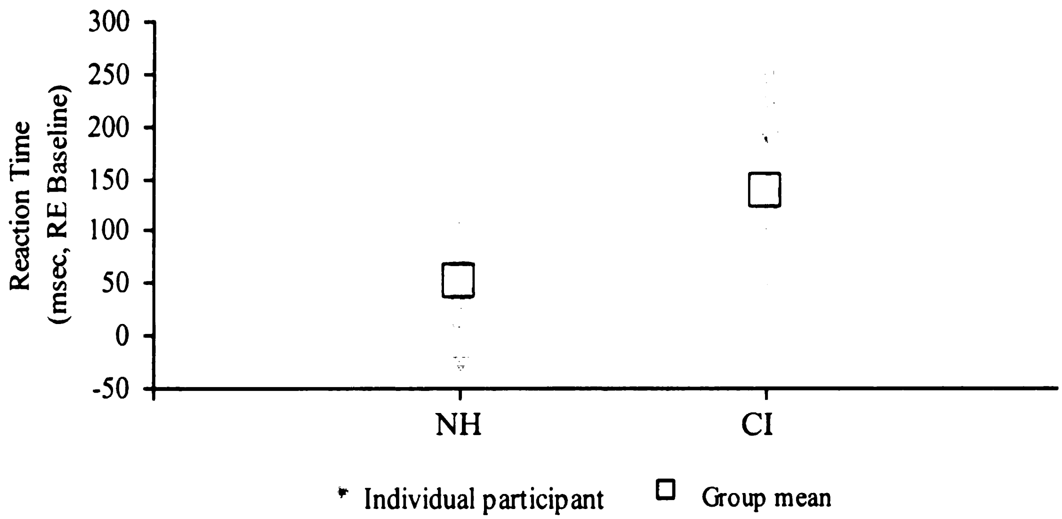

Figure 3-6b. Visual reaction time difference scores in both groups in +5dB S/N.

Additional Dual-task Tests

Cochlear implant listeners: testing at S/N = +10 dB.

After completing testing at +5dB S/N, several of the CI participants (n=6) were tested at +10 dB S/N. It was clear that understanding speech at +5dB S/N was difficult for CI users as a group, and almost impossible for several of the individual participants. The goal here was to investigate whether CI users might be able to perceive speech with greater accuracy as a group when listening at +10 dB S/N. Also, the cognitive effort needed to perceive speech at this S/N was assessed.

Speech perception test results.

Raw scores and normalized scores. Figure 3-7a shows the speech perception raw scores for this test. Figure 3-7b shows the normalized scores. The raw score mean for the CI group was 64% correct, considerably higher than the mean for CI users who listened at +5dB S/N (38% correct). This shows that under dual-task test conditions, CI users can perceive speech with reasonable accuracy when the speech is presented in low-to-mid-level background noise.

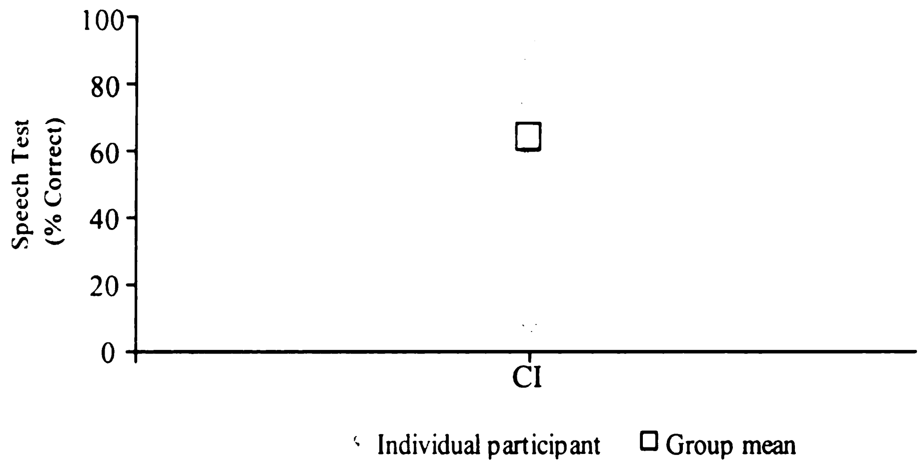

Figure 3-7a. Speech test raw scores for the CI group listening at +10 dB S/N.

The normalized scores mean was much closer to 1.0 for this condition (mean=0.74) than it had been at +5dB S/N (mean=0.43).

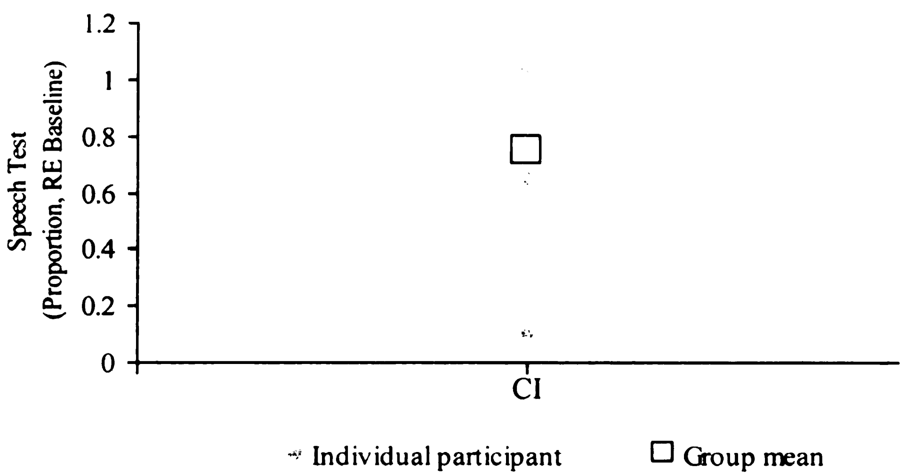

Figure 3-7b. Speech test proportion scores for the CI group listening at +10 dB S/N.

2

Visual reaction time test results.

Raw scores and normalized scores. Figure 3-8a shows the CI users visual reaction time raw scores. The raw score mean found here was 451.7 msec, which is very close to the mean of 445.9 msec reported earlier for the CI users who were tested at S/N=+5 dB. However, when the raw scores shown in figure 3.8a were converted to normalized scores based on the baseline performance of the individual subjects who were tested here, a difference between the present condition and testing at S/N=+5 dB became evident (see Figure 3.8b).

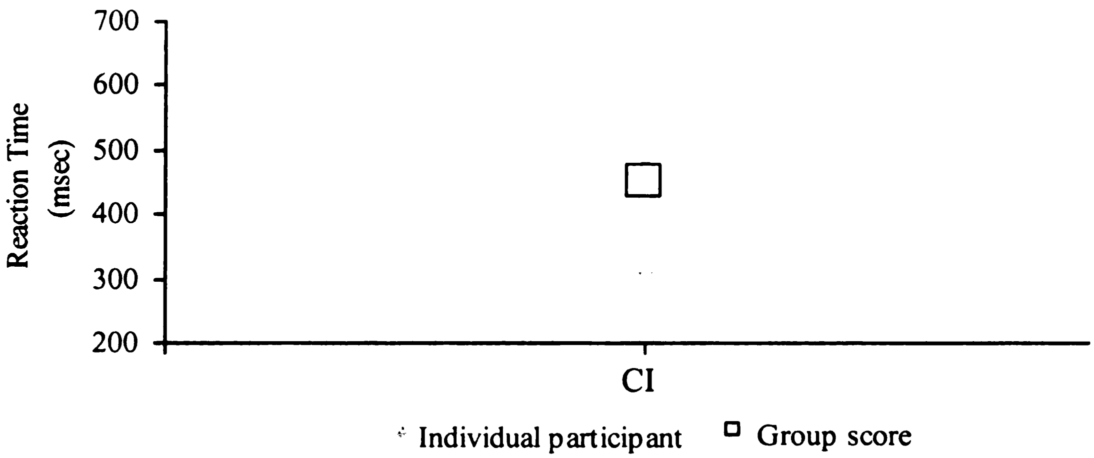

Figure 3-8a. Visual reaction time raw scores in the CI group at +10 dB S/N.

The normalized mean score for S/N=+10 dB was 83.3 msec, well below the mean of 136.8 msec for testing at S/N=+ 5dB. This clearly indicates that CI users were more capable of multi-tasking at 10 dB S/N and, correspondingly, that the cognitive effort needed to perceive speech was measurably reduced here.

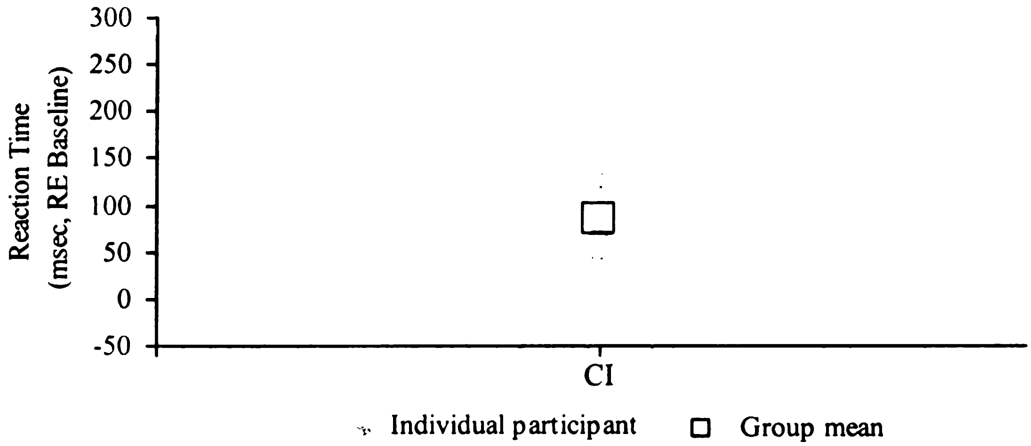

Figure 3-8b.Visual reaction time proportion score in the CI groups at +10 dB S/N.

Normally hearing listeners: testing at S/N = 0 dB.

As noted above, NH listeners were found to perceive speech with high accuracy and minimal cognitive effort when tested at S/N = +5 dB. The level of difficulty of speech listening, therefore, was increased for this new test of NH participants. Specifically, the S/N was set at 0 dB. Eighteen NH listeners (14 of whom had been previously tested at S/N = +5 dB) were tested here.

Speech perception test results.

Raw scores and normalized scores. The NH participants' speech perception raw scores were more variable for this test than seen previously, and also lower on average (see Figure 3.9a below). The mean scores was 81% correct, which was a 15% drop compared to performance at +5dB S/N. A similar pattern was seen for the normalized scores (Figure 3-9b), which fell to a mean of 0.82 here, compared to 0.98 for S/N=+5 dB.

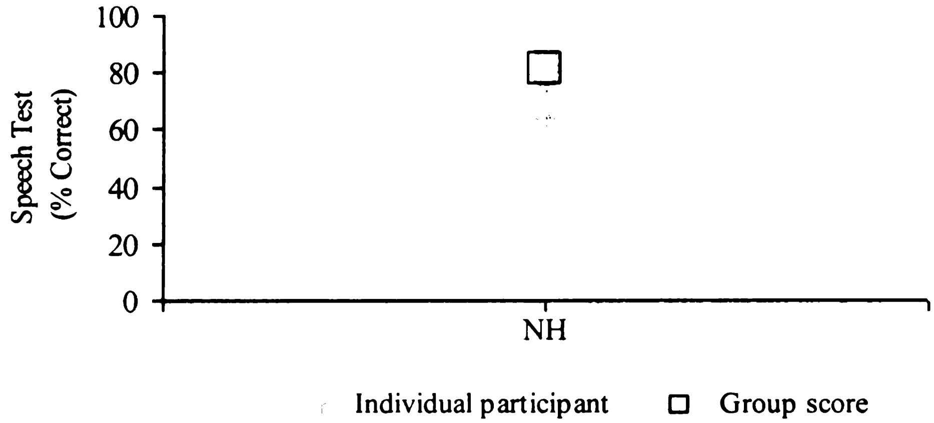

Figure 3-9a. Speech test raw scores for the NH group at 0 dB S/N.

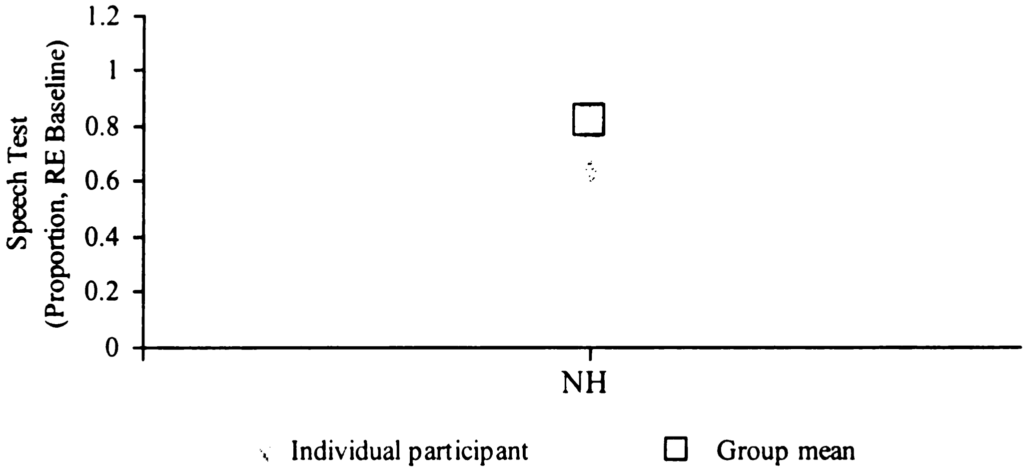

Figure 3-9b. Speech test proportion score for the NH groups at 0 dB S/N.

Visual reaction time test results.

Raw scores and normalized scores. The raw score (Figure 3-10a) and normalized score (Figure 3-10b) visual reaction time results again provide evidence regarding cognitive effort. The mean raw score for this condition was 392.2 msec. The mean normalized score was 80.9 msec. Both of these means are about 30 msec longer than the corresponding means seen for testing at +5 dB S/N. This slowing in visual reaction time performance shows that multi-tasking at 0 dB S/N was measurably more difficult for the NH group. Clearly, 0 dB S/N posed some challenges and, therefore, the visual reaction times tended to be slower at 0 dB than at any other condition tested previously.

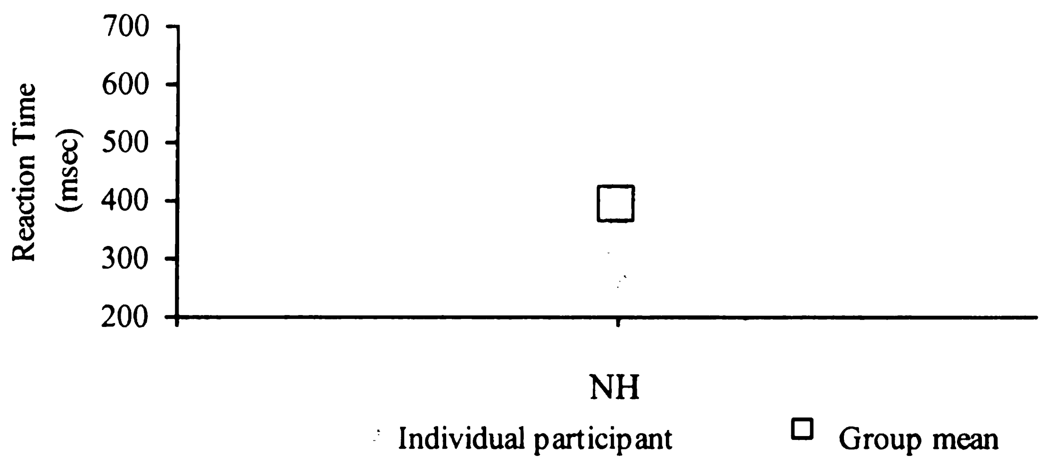

Figure 3-10a. Visual reaction time raw scores for the NH group tested at 0 dB S/N.

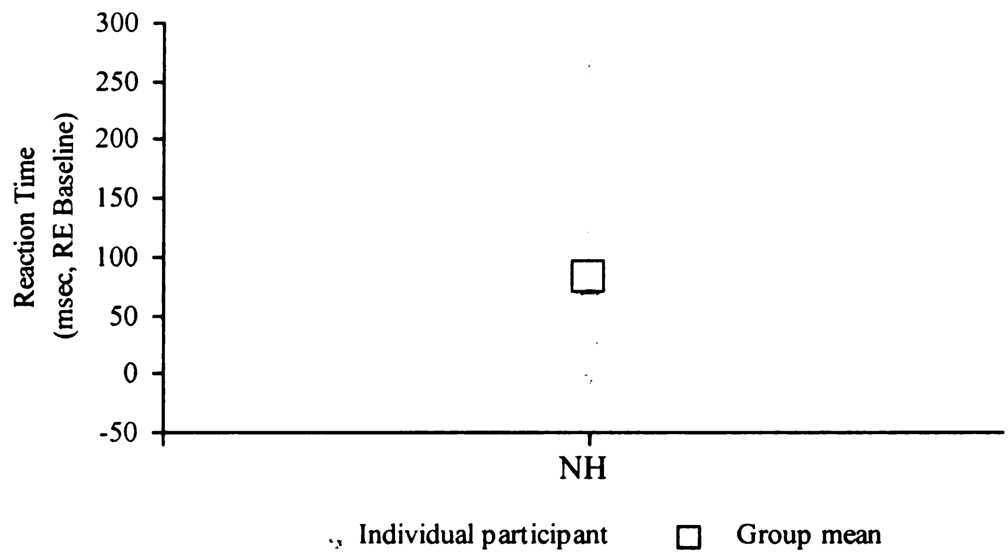

Figure 3-10b. Visual reaction time difference score for the NH group at 0 dB S/N.

The CI Group and the NH Group: A Similar Pattern of Results

This section on Additional Dual Task Tests reported on two tests. The first was a test of CI users conducted at S/N = +10 dB. The second was a test of NH listeners conducted at S/N = 0 dB. The results of those tests proved to be similar in a number of ways. To highlight those similarities the results are re-plotted here side-by-side.

Speech perception test results.

The speech perception raw scores are shown in Figure 3-11a. With the exception of one outlying CI score, the raw scores for the two groups fell in a similar range. The mean scores were 81% for the NH group and 64% for the CI group. The mean computed for the CI group with the outlying score dropped was 75%, which was very close to the NH group mean.

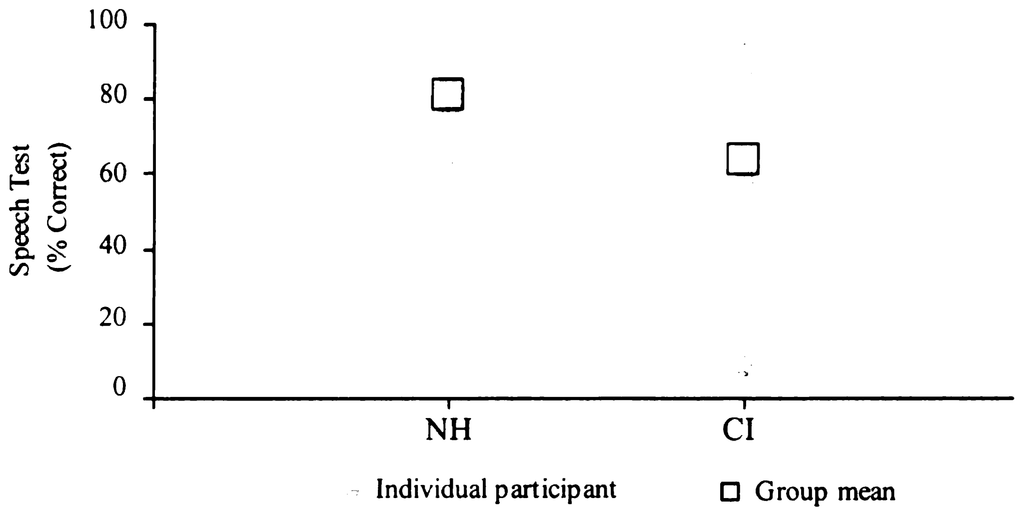

Figure 3-11a. Speech test raw scores for the NH group tested at 0 dB S/N compared to scores for the CI group tested at +10 dB S/N.

The normalized speech perception scores shown Figure 3-11b were, again with one exception (the CI outlier), very comparable. The mean scores for the NH and CI groups were 0.82 and 0.74, respectively.

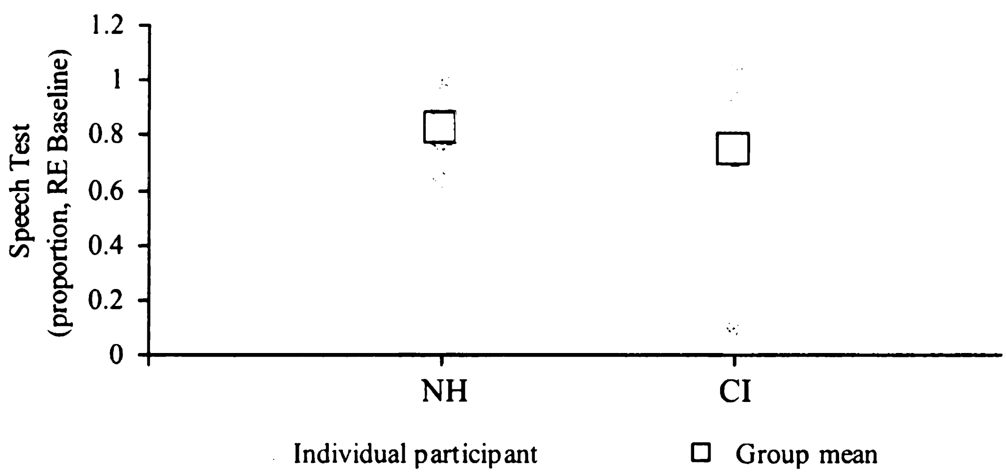

Figure 3-11b. Speech test normalized scores for the NH group tested at 0 dB S/N compared to scores for the CI group tested at +10 dB S/N.

Statistical comparisons of the speech perception scores are shown in Table 3-6. There was a significant difference between the raw scores, but no significant difference between the normalized scores.

Table 3-6. *Comparing speech test scores at: 0 dB (NH) and 10 dB (CI).*

Tested Conditions	t- value	df	Significance	Mean Difference	Std. Error Difference
DT: 0 dB vs. DT: 10 dB	2.38	22	0.03	.18	.07
DT: 0 dB vs. DT: 10 dB (proportional: RE baseline)	0.95	22	0.40	.08	.08

Reaction time test results.

Visual reaction time raw scores from the two groups are shown in Figure 3-12a. The CI group mean (451.7 msec) was about 60 msec higher than the NH mean (392.2 msec), but the ranges of scores for the two groups were very similar. The normalized scores, shown in Figure 3-12b, were even more alike. They matched closely in both mean value (CI mean = 83.3 msec, NH mean = 80.9 msec) and range. There was no significant difference between the group mean results for either the raw reaction times or the normalized times (see Table 3-7).

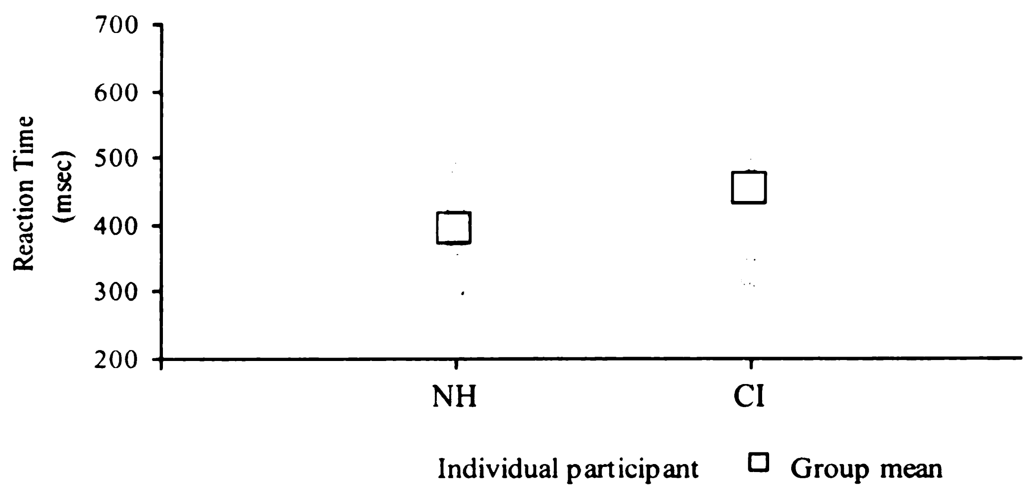

Figure 3-12a. Visual reaction time test raw scores for the NH group tested at 0 dB S/N compared to scores for the CI group tested at +10 dB S/N.

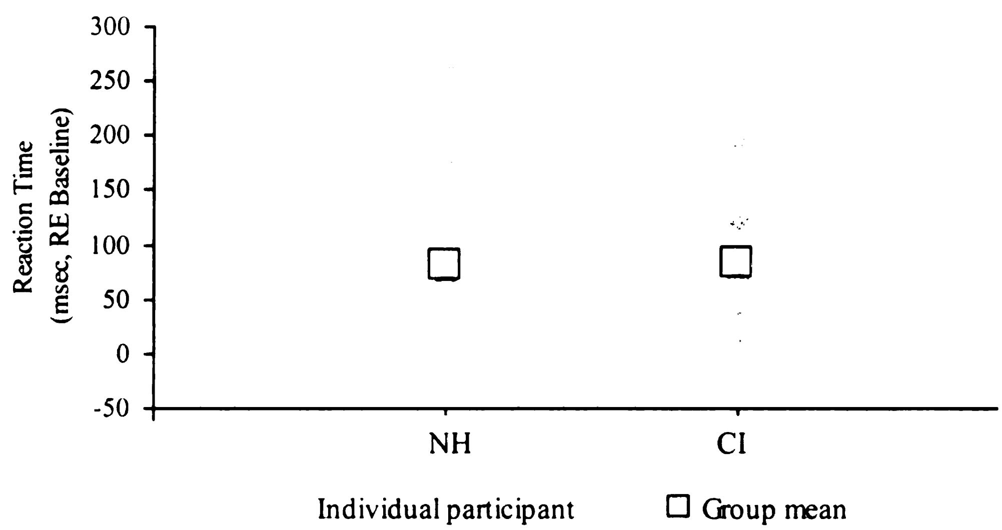

Figure 3-12b. Visual reaction time test normalized scores for the NH group tested at 0 dB S/N compared to scores for the CI group tested at +10 dB S/N.

Table 3-7. *Comparing RT scores at: 0 dB (NH) and 10 dB (CI).*

Tested Conditions	t-value	df	Significance	Mean Difference	Std. Error Difference
DT: 0 dB vs. DT: 10 dB	-1.33	22	.19	-59.48	.20
DT: 0 dB vs. DT: 10 dB (msec., RE baseline)	-.07	22	.95	2.33	.95

Conclusion

Results from comparison analysis show that listening to speech at 0 dB S/N for NH listeners presented similar challenges as listening to speech at +10 dB S/N for the CI users. These results are important for appreciating the challenges that even small amounts of background noise may pose for CI users, in everyday life situations.

CHAPTER 4

Final Thoughts

This study had two parts, a survey and an experiment. This section will discuss clinical implications, limitations, and suggestions for further research regarding each of these. A general summary of the study outcome will also be provided.

Clinical Implications

One potential clinical benefit of the present study is that it provides results that may be useful in counseling individuals with CIs and their spouses and families. When individuals with CIs perform well in speech perception tests that are conducted in a quiet and controlled clinical setting it may be assumed by people surrounding them that they will perform similarly well in real life listening situations. This assumption is a misunderstanding. Listening to speech in quiet is different from listening in noise, and listening in open situations where there may be distractions is different from listening in a controlled environment. It was found here that greater than normal cognitive effort is often exerted by a CI user when perceiving speech in everyday situations, especially if competing noise is present.

Results from the current study indicate that CI users are capable of scoring high in speech recognition tests when listening in low-to-mid level background noise. However, when compared to normally-hearing listeners, more cognitive effort was found to be exerted and more time was found to be needed by CI users to achieve these results. Sharing of findings of this kind with the families of individuals with CIs may help them to develop better understanding of what listening with a CI is like.

A specific finding of the experimental study was that the cognitive demands of listening in moderate background noise could be roughly equated for CI users and NH listeners if the S/N was worsened by 10 dB for the latter group. This suggests the possibility of developing a clinical demonstration in which background noise level is manipulated for normally-hearing listeners to properly model the cognitive challenges faced by a CI user.

Another clinical implication of this study is that the survey results point up the potential importance of using a hearing aid in the opposite ear. Those who used a hearing aid often reported exerting less cognitive effort than those who did not use one, especially when listening in situations that posed special challenges. These results concur with findings from other studies that have documented a binaural hearing advantage. Using a CI combined with a hearing aid in the opposite ear can lead to improved sound localization, improved speech discrimination in noise, and improved overall sound quality (e.g., Tange, Grolman, & Dreschler, 2009).

Finally, clinicians should be aware of the importance of top-down processing skills for speech perception by all CI users, and perhaps especially by older users. Top-down perception refers to perception that relies on prior knowledge and inference from context. An individual's ability to top-down process may affect both the period of acclimation to a new CI and also the long-term benefit that may be derived from sustained CI use. The present survey results suggest that top-down processing skills are generally strong among older CI users, very possibly stronger than those of younger users. This agrees with other CI studies that have found that older age is not a factor that interferes with post-implant results.

Study Limitations

All studies have limitations. The present study has certain limitations which need to be taken into account when considering its contributions. Addressing some of these limitations can be seen as fruitful avenues for future research. This section will discuss separately the limitations of the survey and the experiment.

Survey.

The first limitation in the survey was the juxtaposition of some of its questions. For example, three questions regarding listening in various levels of background noise were presented in succession (Question 6a-6c). This was done to make the survey as straightforward as possible for participants. It is possible that ordering the questions in this way may have also introduced some element of bias to the responses.

Another limitation in the survey is that it was retrospective. The biggest problem in a retrospective study is that some of the information may be hard to get because it relies on participants recalling things that may have happened years ago. The survey participants had worn their CI's an average of 2 years, and they were asked to rate experiences as for back in time as pre-implant. Memory is a selective thing, and it can introduce biases.

A third limitation of the survey is that data were collected here from a single cochlear implant program. The participants' responses could conceivably have been affected in some way by their specific experiences as patients of the University of Michigan Cochlear Implant Program. In a future study, collecting data from individuals associated with multiple clinics could provide answers from a more heterogeneous group and more representatively sample the experiences of CI users.

The last survey limitation concerns financial incentives. No incentives were offered to the participants in this study. The participant response rate was 138/ 260 (53%). Although this rate was substantial, offering incentives could possibly have increased it.

Experiment.

The first limitation in the experiment was the age range of the participants. The majority of the participants were older adults (mean age = 51.8 years). Results might have been in some way biased because of this age effect. Cognitive effort hypotheses postulate age differences in the demands of memory processing to be one factor underlying age-related deficits (Benjamin, 2005; Macht & Buschke, 1983). Memory processing in particular may demand more cognitive effort from older adults (Craik & Simon, 1980; Naveh-Benjamin, 2005).

The second limitation was related to the CI devices worn by the participants. All participants used a multichannel implant; however their CI's differed in their processing strategies and manufacturers. The specifics of the devices themselves were not compared in this study. Possibly, differences in the processing strategies or the manufacturers could have accounted for some portion of the variability among CI users seen here.

Suggestions for Further Research

Measures of cognitive effort have previously been found to provide a useful complement to audiometric tests when assessing listeners with hearing loss in the mild to severe range. The present study demonstrates that studies of cognitive effort may also be informative regarding individuals with profound hearing loss who are CI users. Various investigations could be extended from the present study. Future studies could address three recommended topics: the cognitive effort requirements of bilateral CI users, the cognitive effort requirements of children using CIs, and the benefits of using a hearing aid in the non-implanted ear.

Summary

A survey of was conducted to answer the following question: Do postlingually deafened CI users commonly report having to exert cognitive effort in order to perceive speech when listening in everyday situations? It was found that they do. They specifically reported having to exert special effort whenever background noise is present, when listening to an unfamiliar topic of conversation or an unfamiliar talker (or talkers), and when listening to a non-native speaker or a rapidly speaking talker. Cognitive effort was generally reported to increase when listening in situations where any of these challenges became extreme (e.g., when the background noise level was high). Finally, participants reported that the cognitive effort needed to perceive speech declined rapidly over the first few days and weeks post-implant, and declined more gradually for several months thereafter.

Comparisons of the responses provided by different subgroups (e.g., males vs. females, younger vs. older CI users) provided evidence of the following significant trends. When listening to speech in good conditions (e.g., low noise, single familiar talker) females reported exerting less effort than males, younger participants reported exerting less effort than older participants, and progressive onset participants reported exerting less effort than sudden onset participants. For listening under the most

challenging conditions, CI users who regularly wear a hearing aid in the opposite ear reported exerting significantly less effort than those who do not use a hearing aid.

An experiment was conducted to determine whether postlingually-deafened adults using a CI showed evidence of expending extra cognitive effort compared to that of normally-hearing (NH) listeners when perceiving speech in quiet and in various levels of background noise. Findings indicated that under favorable conditions (listening in quiet, listening at a signal-to-noise ratio of +15 dB), CI users were able to maintain substantial accuracy in their speech perception performance, nearly as high as that of NH listeners. However, the cognitive effort required to perceive speech was substantially greater for the CI group than the NH group. As the background noise level increased, CI users made an increasing number of speech perception errors and, at the same time, showed evidence of a far greater than normal commitment of cognitive effort to speech processing. Finally, it was found that a group of NH listeners tested at S/N = 0 dB and a group of CI users tested at S/N = +10 dB had similar overall results regarding both speech perception and cognitive effort. Hence, the two groups could be roughly equated by a 10 dB difference in S/N.

Findings from the present study indicate that analyzing cognitive effort is both feasible and useful when investigating CI users. Results from this type of measurement can give a clearer idea about how CI users may function in everyday multi-tasking listening situations, rather than just in the testing booth.

TH

APPENDIX A

Survey

Copy of the survey. Descriptive statistics regarding the participants' responses to each question are provided. Abbreviations: N= number of participants; NR= number who gave no response; NO= number who chose "no opinion" option; Mn=mean; Sd= standard deviation.

Listening Effort in Late-Deafened Cochlear Implanted Adults:

A Research Study

Please return your completed questionnaire in the enclosed envelops to:

Rana Alkhamra
Oyer Speech-Language-Hearing Clinic
101 Wilson Road
Michigan State University
Eat Lansing Michigan, MI 48824-1220

We would like to survey you regarding how effortful (hard) / effortless (easy) you find listening to be in different situations. Please, answer the following questions:

Listening Effort in Late-Deafened Cochlear Implanted Adults : A Research Study

We would like to survey you regarding how hard/ effortful you find listening to be in different situations. Therefore, please answer the following questions:

START HERE:

Listening effort using a cochlear implant

1. **BEFORE getting your cochlear implant, was listening to speech effortful or effortless?**

   - ☐ Strongly effortful
   - ☐ Somewhat effortful
   - ☐ Neither effortful nor effortless
   - ☐ Somewhat effortless
   - ☐ Strongly effortless
   - ☐ No opinion

   N=124
NR=0
NO=3
Mn=1.26
Sd=0.78

2. **During the first week AFTER getting your cochlear implant, did listening to speech become more or less effortful than it was before the implant?**

   - ☐ Strongly more effortful
   - ☐ Somewhat more effortful
   - ☐ Neither more nor less effortful
   - ☐ Somewhat less effortful
   - ☐ Strongly less effortful
   - ☐ No opinion

   N=119
NR=0
NO=8
Mn=3.67
Sd=1.20

3. **During the first three to six months AFTER getting your cochlear implant, did listening to speech become more or less effortful than it was before the implant?**

   - ☐ Strongly more effortful
   - ☐ Somewhat more effortful
   - ☐ Neither more nor less effortful
   - ☐ Somewhat less effortful
   - ☐ Strongly less effortful ☐
   - ☐ No opinion

   N=125
NR=0
NO=2
Mn=4.40
Sd=0.85

4. **After using your cochlear implant for six months or longer, did listening to speech become more or less effortful than it was before the implant?**

☐ Strongly more effortful
☐ Somewhat more effortful
☐ Neither more nor less effortful
☐ Somewhat less effortful
☐ Strongly less effortful ☐
☐ No opinion

N=124
NR=0
NO=3
Mn=4.62
Sd=0.77

5. **Did speech listening become more or less effortful when you became more accustomed to hearing speech with your cochlear implant?**

☐ Strongly more effortful
☐ Somewhat more effortful
☐ Neither more nor less effortful
☐ Somewhat less effortful
☐ Strongly less effortful ☐
☐ No opinion

N=125
NR=0
NO=2
Mn=4.49
Sd=0.92

6. **Using your cochlear implant, how effortful or effortless do you describe listening in the following situations:** ***Note that numbers 1 through 6 correspond to the following***

1= Strongly effortful
2= Somewhat effortful
3= Neither effortful nor effortless
4= Somewhat effortless
5= Strongly effortless
6= No opinion

(*Please, mark ONE box for each statement*)

	1	2	3	4	5	6
a. In quiet settings	☐	☐	☐	☐	☐	☐
	N=123	NR= 0	NO= 4	Mn=4.44	Sd=1.04	
b. In settings with a low level of noise	☐	☐	☐	☐	☐	☐
	N=125	Nr==0	NO=2	Mn=3.87	Sd=1.13	
c. In settings with a medium level of noise	☐	☐	☐	☐	☐	☐
	N=126	NR=0	NO=1	Mn=2.94	Sd=1.25	

Continued/ Question # 6 ***(Numbers 1 through 6 correspond to the following)***

1= Strongly effortful
2= Somewhat effortful
3= Neither effortful nor effortless
4= Somewhat effortless
5= Strongly effortless
6= No opinion

	1	2	3	4	5	6
d. In settings with a high level of noise	☐	☐	☐	☐	☐	☐
	N=125	NR=0	NO=2	Mn=1.74	Sd=1.13	
e. When background noise is environmental sounds (e.g., car horn, printer, telephone ringing)	☐	☐	☐	☐	☐	☐
	N=126	NR=0	NO=1	Mn=2.21	Sd=1.15	
f. When background noise is speech sounds (e.g., in a restaurant, in family gatherings)	☐	☐	☐	☐	☐	☐
	N=125	NR=1	NO=1	Mn=2.0	Sd=1.01	
g. When familiar with the conversation topic	☐	☐	☐	☐	☐	☐
	N=124	NR=2	NO=1	Mn=3.41	Sd=1.26	
h. When unfamiliar with the conversation topic	☐	☐	☐	☐	☐	☐
	N=126	NR=0	NO=1	Mn=2.40	Sd=1.22	
i. When in a one-to-one conversation with a familiar speaker	☐	☐	☐	☐	☐	☐
	N=123	NR=0	NO=4	Mn=4.21	Sd=1.13	
j. When in a one-to-one conversation with an unfamiliar speaker	☐	☐	☐	☐	☐	☐
	N=124	NR=2	NO=1	Mn=3.38	Sd=1.21	

Continued/ Question # 6 ***(Numbers 1 through 6 correspond to the following)***

1= Strongly effortful
2= Somewhat effortful
3= Neither effortful nor effortless
4= Somewhat effortless
5= Strongly effortless
6= No opinion

	1	2	3	4	5	6
k. When in a group conversation with familiar speakers	☐	☐	☐	☐	☐	☐
	N=125	NR=1	NO=1	Mn=2.71	Sd=1.28	
l. When in a group conversation with unfamiliar speakers	☐	☐	☐	☐	☐	☐
	N=126	NR=0	NO=1	Mn=2.16	Sd=1.32	
m. When listening to someone who speaks slower than normal	☐	☐	☐	☐	☐	☐
	N=124	NR=1	NO=2	Mn=4.15	Sd=1.14	
n. When listening to someone who speaks faster than normal	☐	☐	☐	☐	☐	☐
	N=125	NR=1	NO=1	Mn=2.44	Sd=1.23	
o. When listening to someone using English as a first language	☐	☐	☐	☐	☐	☐
	N=122	NR=2	NO=3	Mn=3.83	Sd=1.25	
p. When listening to someone who speaks with a foreign accent	☐	☐	☐	☐	☐	☐
	N=117	NR=0	NO=10	Mn=2.22	Sd=1.14	

Continued/ Question # 6 *(Numbers 1 through 6 correspond to the following)*

1= Strongly effortful
2= Somewhat effortful
3= Neither effortful nor effortless
4= Somewhat effortless
5= Strongly effortless
6= No opinion

	1	2	3	4	5	6
q. When listening to someone using your native language	☐	☐	☐	☐	☐	☐
	N=117	NR=2	NO=8	Mn=3.82	Sd=1.32	
r. When listening to someone familiar on the telephone	☐	☐	☐	☐	☐	☐
	N=114	NR=4	NO=9	Mn=3.27	Sd=1.49	
s. When listening to someone unfamiliar on the telephone	☐	☐	☐	☐	☐	☐
	N=112	NR=5	NO=10	Mn=2.24	Sd=1.29	

7. How effortful or effortless is identifying a topic in a conversation when you are listening and working on something else that demands your attention (e.g., taking notes in a meeting, driving a car)?

- ☐ Strongly effortful
- ☐ Somewhat effortful
- ☐ Neither effortful nor effortless
- ☐ Somewhat effortless
- ☐ Strongly effortless
- ☐ No opinion

N=122
NR=1
NO=4
Mn=2.09
Sd=1.08

8. How often do you ask speakers to rephrase or repeat their original utterance when you are listening and working on something else that demands your attention (e.g., taking notes in a meeting, driving a car)?

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=127
NR=0
NO=0
Mn=2.83
Sd=0.70

9. **Do you wear a hearing aid in the ear opposite to the implanted ear?** → (If never, go to question 11)

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=124
NR=2
NO=1
Mn=4.29
Sd=1.45

10. **Do you find that using a hearing aid in conjunction with your cochlear implant makes it more difficult or more easy to understand speech?**

- ☐ Strongly more easy
- ☐ Somewhat more easy
- ☐ Neither more easy nor more difficult
- ☐ Somewhat more difficult
- ☐ Strongly more difficult
- ☐ No opinion

N=30
NR=13
NO=84
Mn=2.80
Sd=1.49

11. **Does lipreading become especially important when you are trying to understand speech in QUIET or in NOISY listening situations?**

- ☐ Strongly important in quiet
- ☐ Somewhat important in quiet
- ☐ Neither important in quiet nor in noise
- ☐ Somewhat important in noise
- ☐ Strongly important in noise
- ☐ No opinion

A consistency question. The majority gave 2 different answers. Information is in questions are 12&13

12. **Do you use lipreading to enhance speech understanding in QUIET listening situations?**

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=126
NR=1
NO=0
Mn=2.98
Sd=1.15

13. Do you use lipreading to enhance speech understanding in NOISY listening situations?

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=127
NR=0
NO=0
Mn=2.27
Sd=1.32

14. Do you find that lipreading increases or decreases listening effort?

- ☐ Strongly increases
- ☐ Somewhat increases
- ☐ Neither increases nor decreases
- ☐ Somewhat decreases
- ☐ Strongly decreases
- ☐ No opinion

N=112
NR=1
NO=14
Mn=2.93
Sd=1.33

15. Please indicate how often, on average, you spend most of your time communicating with family and friends

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=127
NR=0
NO=0
Mn=1.91
Sd=0.81

16. Please indicate how often, on average, you spend most of your time communicating with unfamiliar people (e.g., building genitor, grocery worker, restaurant waiter)?

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=126
NR=1
NO=0
Mn=2.70
Sd=0.77

Hearing History

17. What is the cause of your hearing loss (if known)?......................

18. Was your hearing loss

☐ Sudden
☐ Became worse with time

N=127
NR=0
NO=0
Mn=1.79
Sd=0.41

19. At what age was your hearing loss identified?

A Right ear---------------------
B Left ear ----------------------

A	B
N=118	N=118
NR=7	NR=7
NO=2	NO=2
Mn=25.69	Mn=26.61
Sd=19.48	Sd=19.88

20. At what age did your hearing loss become severe-to-profound?

A Right ear---------------------
B Left ear ----------------------

A	B
N=116	N=113
NR=9	NR=10
NO=2	NO=4
Mn=40.31	Mn=40.27
Sd=21.03	Sd=19.53

21. At what age did you first use a hearing aid?

A Right ear---------------------
B Left ear ----------------------

A	B
N=104	N=93
NR=5	NR=7
NO=18	NO=27
Mn=31.54	Mn=30.01
Sd=18.95	Sd=19.10

22. Before getting your cochlear implant, how often did you use a hearing aid in the IMPLANTED EAR?

☐ All the time
☐ Most of the time
☐ Some of the time
☐ Rarely
☐ Never

N=125
NR=2
NO=0
Mn=2.12
Sd=1.66

23. Before getting your cochlear implant, how often did you use a hearing aid in the ear OPPOSITE to the implanted ear?

- ☐ All the time
- ☐ Most of the time
- ☐ Some of the time
- ☐ Rarely
- ☐ Never

N=125
NR=2
NO=0
Mn=2.52
Sd=1.82

24. Which ear is your cochlear implant in?

- ☐ Right ear
- ☐ Left ear

N=122
NR=2
NO=3
Mn=1.45
Sd=0.50

25. For how long have you had your cochlear implant?

- ☐ 3- 6 months
- ☐ 7-12 months
- ☐ 13-18 months
- ☐ 19-24 months
- ☐ If more than 2 years, please specify ....

N=124
NR=2
NO=1
Mn=4.67
Sd=0.76

26. Is your vision

Normal → (If normal, go to question 29)
☐ Corrected with lasses

N=123
NR=3
NO=1
Mn=1.79
Sd=0.41

27. If your vision is corrected, do you have more difficulty in

- ☐ Seeing objects/people who are near you
- ☐ Seeing objects/people who are at a distance
- ☐ Seeing objects/people who are near or distant from you

N=78
NR=49
NO=0
Mn=1.96
Sd=0.70

Demographics

28. What is your age? ---------------------------

N=121
NR=6
Mn=64
Sd=16.27

29. Is English your first language?

- ☐Yes,
- ☐No, **please specify your first language**....................

N=125
NR=2
Mn=1.03
Sd=10.96

30. What is the highest level of education that you have completed?

- ☐Elementary school
- ☐Junior high school
- ☐High school / vocational high school
- ☐Some college
- ☐4 years college
- ☐More than 4 years of college

N=125
NR=2
Mn=4.09
Sd=10.75

31. Please check the best description of your employment status.

- ☐Employed
- ☐Unemployed
- ☐Own your own business
- ☐Student
- ☐Retired
- ☐Other, please specify............................

N=125
NR=2
Mn=3.70
Sd=1.86

APPENDIX B

BKB Test Lists:

BKB Test: Five different stimulus test lists of 32 sentences each are listed below. An individual BKB sentence could appear in one list only. These lists were randomly assigned to the single-task and dual-task test conditions as needed.

BKB Test Lists

List_A

Sentence List 1

The clown had a funny face.
The car engine's running.
She cut with her knife.
Children like strawberries.
The house had nine rooms.
They're buying some bread.

The green tomatoes are small.
He played with his train.
The postman shut the gate.
They're looking at the clock.
The bag bumps on the ground.
The boy did a handstand.
A cat sits on the bed.
The lorry carried fruit.
The rain came down.
The ice cream was pink.

Sentence List 2

The ladder's near the door.
They had a lovely day.
The ball went into the goal.
The old gloves are dirty.
He cut his finger.
The thin dog was hungry.
The boy knew the game.
Snow falls at Christmas.
She's taking her coat.
The police chased the car.
A mouse ran down the hole.
The lady's making a toy.
Some sticks were under the tree.
The little baby sleeps.
They're watching the train.
The school finished early.

List_B

Sentence List 3

The glass bowl broke.
The dog played with a stick.
The kettle's quite hot.
The farmer keeps a bull.
They say some silly things.
The lady wore a coat.
The children are walking home.
He needed his holiday.
The milk came in a bottle.
The man cleaned his shoes.
They ate the lemon jelly.
The boy's running away.
Father looked at the book.
She drinks from her cup.
The room's getting cold.
A girl kicked the table.

Sentence List 4

The wife helped her husband.
The machine was quite noisy.
The old man worries.
A boy ran down the path.
The house had a nice garden.
She spoke to her son.
They're crossing the street.
Lemons grow on trees.
He found his brother.
Some animals sleep on straw.
The jam jar was full.
They're kneeling down.

The girl lost her doll.
The cook's making a cake.
The child grabs the toy.
The mud stuck on his shoe.

List_C

Sentence List 5

The bath towel was wet.
The matches lie on the shelf.
They're running past the house.
The train had a bad crash.
The kitchen sink's empty.
A boy fell from the window.

She used her spoon.
The park's near the road.
The cook cut some onions.
The dog made an angry noise.
He's washing his face.
Somebody took the money.
The light went out.
They wanted some potatoes.
The naughty girl's shouting.
The cold milk's in a jug.

Sentence List 6

The paint dripped on the ground.
The mother stirs the tea.
They laughed at his story.
Men wear long trousers.
The small boy was asleep.
The lady goes to the shop.
The sun melted the snow.
The father's coming home.
She had her pocket money.
The lorry drove up the road.
He's bringing his raincoat.
A sharp knife's dangerous.

They took some food.
The clever girls are reading.
The broom stood in the corner.
The woman tidied her house.

List_D

Sentence List 7

The children dropped the bag.
The dog came back.
The floor looked clean.
She found her purse.
The fruit lies on the ground.
Mother fetches a saucepan.
They washed in cold water.
The young people are dancing.
The bus went early.
They had two empty bottles.

A ball's bouncing along.
The father forgot the bread.
The girl has a picture book.
The orange was quite sweet.
He's holding his nose.
The new road's on the map.

Sentence List 8

The boy forgot his book.
A friend came for lunch.
The match boxes are empty.
He climbed his ladder.
The family bought a house.
The jug stood on the shelf.
The ball broke the window.
They're shopping for cheese.
The pond water's dirty.
They heard a funny noise.
Police are clearing the road.

The bus stopped suddenly.

She writes to her brother.
The footballer lost a boot.
The three girls are listening.
The coat lies on a chair.

List_E

Sentence List 9

The book tells a story.
The young boy left home.
They're climbing the tree.
She stood near her window.
The table has three legs.
A letter fell on the mat.
The five men are working.

The shoes were very dirty.
He listens to his father.
They went on holiday.

Baby broke his mug.
The lady packed her bag.
The dinner plate's hot.
The train's moving fast.
The child drank some milk.
The car hit a wall.

Sentence List 10

A tea towel's by the sink.
The cleaner used a broom.
She looked in her mirror.
The good boy's helping.
They followed the path.
The kitchen clock was wrong.
Someone's crossing the road.
The postman brings a letter.
The dog jumped on the chair.
They're cycling along.
He broke his leg.
The milk was by the front door.
The shirts hang in the cupboard.
The ground was too hard.
The buckets hold water.
The chicken laid some eggs.

Trial List

Sentence List 19

The family like fish
Sugar's very sweet
The baby lay on a rug
The washing machine broke.
They're clearing the table.
The cleaner swept the floor.
The grocer cells butter.
The bath water was warm.

He's reaching for his spoon.
She hurt her hand.
The milkman drives a small van.
The boy slipped on the stairs.
They're staying for supper.
The girl held a mirror.
The cup stood on a saucer.
The cows went to market.

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