1985

Some effects of cochlear implant use on loudness modulation

Carol F. Ross
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AN ABSTRACT OF THE THESIS OF Carol F. Ross for the Master of Science in Speech Communication, with an emphasis in Speech Language Pathology/Audiology, presented November 15, 1985.

Title: Some effects of cochlear implant use on loudness modulation.

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The literature presents a complex model of speech regulation that employs "central imaging" of the motor act of speech preceding production. In addition, this model provides options for regulating speech by sensory feedback. The regulation of intensity relies on feedback more than does

the regulation of the timing aspect of speech. Persons who are adventitiously deaf have varying degrees of success in modulating their vocal intensity. They may rely upon central feedback or, at times, may regulate intensity by using tactile, kinesthetic, or social feedback (Lane and Tranel, 1971). Deaf persons experience difficulty in modulating their vocal intensity appropriately in the presence of background noise. Cochlear implants provide hope for improving the communication skills of persons who sustain profound hearing loss. A cochlear implant is an auditory prosthesis designed to stimulate electrically the surviving population of nerve fibers in the cochlea of a deaf person.

In this study, five deaf individuals with cochlear implants were presented with noise that was manipulated systematically, to test the hypothesis that deaf persons using cochlear prostheses will demonstrate intensity regulation of their vocal output that is more appropriate when their implants are turned on than when turned off. The intensity of their vocal output was measured to determine if they demonstrated a Lombard response, that is, a systematic increase in vocal intensity with increasing intensity of background noise. Results from the study were mixed. With implants on, three subjects made systematic increases in vocal intensity with increasing background noise, while two subjects did not make such increases. In addition, the relation between intensity of vocal output and background

noise was closer to the normal function for the three subjects who demonstrated a Lombard response. The "normal function" was defined by measuring the vocal intensity responses of five normal hearing control subjects who performed the same tasks as the experimental subjects.

The results of this study appear consistent with the growing body of information on the effects of cochlear implants gathered from numerous research centers that indicates there is wide variation in performance that cannot be attributed entirely to implant design (Millar et al., 1984; Miller & Pfingst, 1984). Two important factors that appear to influence performance are the number and placement of remaining nerve fibers and the cognitive style employed by the individual.

At present the number and functioning of the remaining nerve fibers can be estimated roughly from a battery of psychophysical tests, including electrical stimulation of the cochlea, administered prior to implantation. There is a need to enlarge the scope of pre-implantation tests that will be predictive of successful implant use. The results of this study suggested that those individuals who achieve significant benefit from a cochlear implant also may demonstrate a Lombard response. These findings imply that testing for presence of a Lombard response during pre-implant electrical stimulation may be predictive of successful implant use.

SOME EFFECTS OF COCHLEAR IMPLANT USE
ON LOUDNESS MODULATION

by

CAROL F. ROSS

A thesis submitted in partial fulfillment of the
requirements for the degree of

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Portland State University

1985

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

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CHAPTER I

INTRODUCTION AND STATEMENT OF PURPOSE

Profound hearing loss is a major health care problem that has far reaching impact upon the individuals experiencing it and upon their families (Stevens, 1982).

Wexler, Miller, Berliner, and Crary (1982) comment:

Illness is a social event as well as a biological one. Its impact extends beyond the victim, in adversely affecting the lives of people with close ties to the patient. When the disaster of profound deafness strikes, those closest to the patient feel helpless. Anxiety, panic, depression and anger are the common emotional accompaniment of this state of affairs.

Ramsdell (1958) outlined clearly the three psychological levels of hearing and the resulting disturbances experienced when hearing is lost. The most significant, yet rarely recognized condition, is loss of hearing at the primitive level which leads to loss of feeling of relationship with the world. Ramsdell suggested this is a major cause of the feeling of "deadness" and depression reported by patients who have experienced sudden deafness. The second level of auditory function is called the signal or warning level. Loss of this function leads not only to decreased awareness of those environmental dangers signalled by sound, but also to loss of the aesthetic experience of sound. The impact of

loss of hearing at the third, or symbolic level, leads to reduced social and communication competency. Those who are deaf demonstrate significant communication problems because of the decreased ability to understand verbal messages accurately and decreased ability to communicate efficiently.

Rousey (1971) suggested "the hearing impaired individual might experience major anxieties about what those in his environment think of him." Based on his wide clinical experience with the post-lingually deaf, Edgerton (1985) commented that they often "feel extremely insecure regarding the appropriateness of their speech loudness level for most social interactions."

The issue of loudness regulation following onset of deafness forms the focal point of this study. Virtually all individuals with profound hearing loss have difficulty monitoring their vocal output at times (Penn, 1955). Indeed, persons who are adventitiously deaf may demonstrate deterioration over time of some of the dimensions of speech (Cowie, Douglas-Cowie, & Kerr, 1982; Zimmerman & Rettaliata, 1981). The changes that occur in speech may include articulation inaccuracies, voice quality aberrations, inappropriate stress and pitch pattern, and inappropriate voice loudness levels (Edgerton, 1985). Fortunately for many, some aspects of speech such as articulation have little dependence upon auditory feedback for regulation and are maintained after onset of deafness (Goehl & Kaufman, 1984).

With the development of cochlear implants, there is hope for improving the communication skills of those who sustain profound hearing loss. A cochlear implant is an auditory prosthesis designed to stimulate electrically the surviving population of nerve fibers in the cochlea of a deaf person. More than five hundred persons with profound hearing loss have received cochlear implants to date. The early single-channel prostheses gave implanted patients a rough perception of environmental sounds and provided cues for speechreading. Evaluation of these single-channel implants has shown some improvement in the hearing performance of subjects with the prosthesis. In a germinal study conducted by Bilger (1977), electroacoustic measurements were obtained on subjects implanted with a single channel prosthesis.

Bilger reported:

The loudness data for these three subjects seem to indicate that subjects fitted with implanted auditory prostheses can have relatively normal appreciation for the loudness of at least low-frequency sounds.

The American Medical Association Council on Scientific Affairs (1983) reported:

It is generally agreed that profoundly deaf persons who experienced deafness after they had developed language skills...obtain the following benefits from cochlear implants 1) better contact with environmental sounds...2) awareness of when a person is speaking, 3) help in speech-reading, and 4) help in modulation of their own voice.

Within the last five years, several second-generation

cochlear implants have been approved by the Food and Drug Administration for investigational clinical trials. These newer prostheses include multiple-channel implants as well as extra-cochlear implants. Preliminary experience with these second-generation prostheses suggests that the implanted subjects demonstrate improved ability to hear environmental sounds, improved speech-reading skills, more acceptable speech output, and for some, the ability to understand substantial amounts of conversational speech using electrical stimulation alone (Millar, Tong, & Clark, 1984; Miller, 1985).

Five subjects have been implanted with cochlear prostheses at Good Samaritan Hospital and Medical Center, Portland, Oregon. Much of the time they demonstrate an ability to modulate their vocal loudness levels appropriately, as observed in the Rehabilitation Institute of Oregon Outpatient Clinic and as noted in patient and family reports. Occasionally, the implanted subjects and their families report inconsistent "lapses" of control. The subjects express embarrassment over speaking too loudly or softly in various circumstances. There is sufficient inconsistency in their vocal loudness regulation to question whether the subjects are receiving adequate acoustic information on which to base judgments for loudness.

Detailed studies to determine the effect of a cochlear implant on a subject's speech output have not been conducted.

Supporting data are needed before clinicians can justifiably expect the implanted subjects to use information provided by their implants to modify appropriately their vocal loudness in response to environmental sound levels.

Statement of Purpose

The purpose of this study was to investigate the following hypothesis: If a cochlear prosthesis provides adequate information regarding the intensity of environmental sounds to a deaf patient, and if this prosthesis also provides adequate information regarding the intensity of his own vocal output, then it should be possible to demonstrate and to measure vocal output for these persons that is more appropriate with the prosthesis operating than pre-operatively or with the cochlear implant turned off. The investigation sought to answer two questions: 1) Will a systematic, measureable change occur in the voice intensity of a person with a cochlear implant when the subject is exposed to background noise that is manipulated systematically? 2) For the cochlear implant patient, is the relation between intensity of vocal output and background noise closer to the normal function when the implant is turned on than when turned off?

CHAPTER II

REVIEW OF THE LITERATURE

Overview

At first glance the issue of voice intensity regulation appears simple. Ask a group of persons "How do you know how loudly to talk?" Individuals may respond: "I talk as loudly as called for by the occasion," or "I choose a level that feels right," or "I talk so I can be heard." This "intuitive knowing" of appropriate intensity output is based on hearing oneself talk in social situations and receiving feedback from listeners about circumstances that enhance communication (Carhart, 1947). This learning takes into account elementary laws of physics; for example, "sound pressure decreases 6 dB with each doubling of distance" (Hodgson, 1977). A speaker learns to raise his voice when the listener is at a distance.

In the formative years, loudness modulation is learned from repeated experiences in fine tuning the auditory, tactile, and proprioceptive feedback mechanisms. Information on how the ear perceives intensity and how it interprets changes in intensity is helpful in understanding the dynamics of intensity regulation. In addition, researchers are identifying the factors or cues that play an influential role

in voice regulation.

Individuals who become deaf often experience lapses in control of loudness. Penn (1955) sampled two hundred persons with hearing losses and found that many demonstrated an occasional vocal intensity level that was disturbingly loud, insufficiently loud, or had unplanned fluctuation in loudness. However, it has been observed that persons who are deaf demonstrate loudness modulation appropriately much of the time. It may be assumed that certain mechanisms continue to operate to maintain appropriate loudness under the condition of changed auditory feedback. An overview is offered of alternate feedback mechanisms that may provide such compensation following sensory deprivation. Indeed, an indepth examination of intensity regulation leads the reader into the controversial issue of how the various aspects of speech, especially loudness, are maintained or regulated once learned.

This study is specifically concerned with the issue of loudness modulation in a population of persons with profound hearing loss who have been implanted with a cochlear prosthesis. A historical perspective of electrical stimulation of the cochlea is offered along with specific descriptions of the second generation cochlear implants worn by the subjects in this study. Differences are reviewed between the ear's response to being stimulated electrically as compared to its response to being stimulated acoustically.

The main thrust of this study is an investigation of the breakdown of loudness modulation following complete loss of hearing and the role of the cochlear implant in providing information to aid in regaining appropriate loudness modulation. The special problem of how to measure the potential for appropriate loudness modulation in a functional setting using a cochlear implant is raised. A discussion of the Lombard sign as a response that is representative of the functional behavior to be studied is offered. It is apparent that the information needed to provide a comprehensive picture of loudness modulation following a cochlear implant comes from diverse areas of study. One such area is the perception of loudness.

Loudness Perception

Sound is measured physically in terms of power. The acoustic power of the faintest 1000-Hz tone that can be heard by a healthy ear is 0.000 000 000 000 000 1 watt per square centimeter. The acoustical engineer measures sound intensity in terms of pressure (which is proportional to the square root of the power of the sound). The faintest 1000-Hz tone audible to the healthy ear has an acoustic pressure of 0.0002 micro Pascals. The decibel scale was developed to deal conveniently with such unwieldy numbers. This logarithmic system has no fixed value point but instead represents a

ratio of one acoustic power to the other. The bel is a logarithm unit indicating ten-fold the power of the reference sound. For added convenience this scale uses one-tenth of a bel, or decibel, as the unit to compare sound powers to one another. The decibel is defined as the ratio between two powers (Davis, 1970).

The preceding description deals with the physical measurement of sound intensity. Psychoacoustics is the study of the relation of auditory sensations (how humans perceive sound) to the physical property of the acoustic stimuli. Loudness is the auditory perception that relates to the physical intensity of a sound.

The need for a scale to measure loudness became apparent to Stevens (1955) who reported:

Not long after they had developed the conventional decibel scale for measuring sound intensity, the engineers noted that equal steps on the decibel scale do not sound like equal steps and that a level of 50 dB does not sound like half of 100 dB....It was soon realized that there was a need for a scale whose numbers made more sense to the (average person) than do the numbers on the decibel scale.

Stevens (1959) developed such a scale for loudness (a subjective measure) and related it to intensity (a physical measure). He did extensive research in the measurement of sensation before choosing the measurement method for loudness. In carefully-reasoned articles, Stevens (1955, 1959) proposed using a magnitude scale (as opposed to a category scale or a just-noticeable-difference scale) to

describe loudness. He chose a magnitude scale because loudness perceptions correlate with the addition of excitation to excitation at the physiological level. This is in contrast to pitch perceptions which correlate with the substitution of excitation for excitation at the physiological level. He instructed his subjects to estimate the magnitude of a stimulus sound in terms of half loudness, double loudness, and so on, in comparison to a reference sound and to assign numbers to reflect values of the perceived loudness of the sounds. The resultant sone scale standardized the relationship between loudness and intensity. The sone scale is a power function scale based on magnitude estimation. The scale's outcome shows loudness grows approximately as the 0.6 power of the sound pressure at 1000-Hz (Lane, Catania, & Stevens, 1961). In other words, the sound pressure from an external source must be more than tripled for a subject to perceive a doubling in loudness. An interesting phenomenon occurs when the sound source is generated by the subject himself. Under that condition, the subject perceives a doubling in loudness when the sound pressure level is less than doubled (Lane et al., 1961).

A speaker's judgment of his own voice intensity is called his autophonic response. Lane et al. (1961) raised the question: "Is the loudness scale different for a listener who is also his own source of sound?" These

authors used the method of magnitude estimation to develop a subjective scale similar to the sone scale for measuring the autophonic response. The resultant autophonic scale relates the speaker's estimate of his own voice level to the sound pressure level produced (Lane, 1963). Lane et al. (1961) found the autophonic scale grows approximately as the 1.1 power of the actual sound pressure. Comparing the results of the two scales, the authors concluded:

When the speaker raises his voice by what he judges to be a factor of two, his voice will not sound twice as loud to a listener. In other words, there is a great difference from the subject's point of view between the relative subjective magnitude of sounds that he generates by his own vocal effort and those that are generated by an external source.

A speaker judges the loudness of his own voice from the airborne sound (air sidetone), from his head sidetone, and from proprioceptive cues. When he listens to sounds other than those he generates, he bases his loudness judgment on airborne sound. Thus, using different cues for judging loudness may be a source of the disparity between autophonic loudness judgments and external sound source loudness judgments. The conclusion of this review on loudness perception leads naturally to the topic of loudness regulation.

Loudness Modulation

Carhart (1947) wrote concerning loudness modulation:

"We tend to maintain a favorable margin between the loudness of our speech and the background noise without talking so that our listeners find our speech unpleasantly loud." A speaker unconsciously raises his voice when background noise increases and lowers his voice when he speaks in a quiet room; both maneuvers are accomplished without much effort and with seeming inattention to the matter.

Hanley and Steer (1949) tested their hypothesis that people "naturally" make appropriate adjustments to difficult communication situations. They found their untrained subjects reduced their rate of speaking, prolonged syllables, and spoke with greater intensity as competing noise increased. The researchers concluded that this was a "desirable manner" of reacting to noise in order to insure improved intelligibility.

It is evident from the sone scale and the autophonic scale that listeners do not compensate for changes in the way they hear sound (either self-generated or from an external source) with equal-step changes in intensity of vocal output. From this observation, Lane, Tranel, and Sisson (1970) found evidence to support a theory that speaking and listening rely on separate sensory systems for operation.

Many researchers have attempted to quantify the expected increase in voice intensity with increasing intensity of background noise. They found that an increase

is predictable, but that the ratio of change varied from 0.2 to 0.5 dB vocal intensity increase per dB of noise increase among various researchers (Black, 1951; Charlip & Burk, 1969; Dreher & O'Neill, 1957; Garber, Siegel, Pick, & Alcorn, 1976; Hanley & Steer, 1949; Korn, 1954; Ringel & Steer, 1963; Siegel & Pick, 1974; Siegel, Pick, Olsen, & Sawin, 1976; Taylor, 1949; Waldron, 1960). Siegel, Shork, Pick, and Garber (1982) reported they obtained a ratio of 0.3 dB increase per dB of noise increase. These results are comparable to ratios obtained by Siegel and Pick (1974) and Siegel et al. (1976). Stevens (1955) obtained a larger ratio (slope 0.5) and attributed the variability in results between researchers to the "host of potentially biasing factors" present in loudness regulation studies. These "biasing factors" will be examined in detail later.

Lombard Effect

The direct increase in intensity level of the message as the noise level is increased is called the Lombard effect (or sign) after the French otolaryngologist Etienne Lombard. In the early 1900's, Lombard began a series of experiments based on two commonly noted occurrences: 1) persons with sensorineural hearing losses tend to increase vocal intensity and demonstrated apparent loss of ability to monitor themselves and 2) persons with normal hearing

increase vocal intensity in the presence of noise with poor ability to monitor themselves (Egan, 1971).

Lombard observed the effects of masking noise on normal hearing patients and on bilaterally and unilaterally deaf patients using a noise-inducing device patented by Barany (Lane & Tranel, 1971). Between 1909 and 1911 he published his numerous findings from his series of experiments with masking noise (Sullivan, 1963).

Lombard reached a simple, but important, conclusion that a person engaged in conversation increases his vocal level when presented with noise. In addition, Lombard reported that subjects decrease their voice intensity when the level at which they hear their own voice (their "sidetone") increases. Telephone engineers call this effect the sidetone penalty function; Lane and Tranel (1971) proposed the term "Fletcher function." In current literature it is referred to as the sidetone amplification effect.

Lane and Tranel (1971) asserted that the sidetone amplification effect is a companion phenomenon to the Lombard effect, reflecting the same underlying process. They supported their statement with studies that demonstrated that speakers compensate approximately half way for increases in noise level and they compensate halfway for decreases in their apparent speaking level. Conversely, Siegel et al. (1982) concluded that the correlational data

from their study do not support such a relationship. Similar nonsignificant relationships between the Lombard response and sidetone amplification response were reported by Siegel et al. (1976) and Siegel and Kennard (1984). Siegel, et al. (1982) suggested that the concept of separate feedback systems for various aspects of speech control is supported by the findings that the two responses do not generate equivalent results. They conclude that auditory feedback affects the steady state components and the dynamic (rapidly changing) components of speech production differently. Thus it is not appropriate to generalize on how auditory feedback affects speech but rather how it affects specific components of speech.

Lombard Effect and Research

The Lombard response has been used as the dependent variable in numerous studies despite major drawbacks that limit its usefulness in testing and research. Newby (1958) pointed out that the Lombard sign as a test for hearing loss is not standardized. Waldron (1960) concluded that the rate of presentation of noise (instantaneous compared to gradual introduction) did not have an effect on either naive or sophisticated subjects, but it is not known with certainty what masking level is needed for inducing the voice increase. The Lombard response is highly variable, affecting some markedly and others minimally (Chaiklin &

Ventry, 1963; Dreher & O'Neill, 1957; Gardner, 1966). In addition, a sophisticated (coached) subject can learn to control somewhat the intensity of his voice in the presence of masking noise (Siegel & Pick, 1974; Waldron, 1960). Hanley and Harvey (1965) noted there is no simple technique for quantifying vocal intensity changes. At that time, the authors reported, a VU meter was used sometimes to monitor the level of the patient's voice; more often the examiner made a subjective judgment to detect the presence of the Lombard sign when testing for malingering.

Currently, these drawbacks remain at issue. Standardization is difficult to establish because of the wide variability in individual vocal intensity responses (Chaiklin & Ventry, 1963). Measuring change in intensity rather than measuring absolute intensity values appears to be a more appropriate procedure. Many researchers employ maximum levels of masking starting at 60 dB SPL and increasing to 90-100 dB SPL to elicit a Lombard effect (Siegel & Pick, 1974; Waldron, 1960).

A number of studies have examined the effects of coaching (subject sophistication) upon their test results. Coached or sophisticated subjects have demonstrated controlled Lombard responses; they produce smaller, but still significant, changes in intensity level (Taylor, 1949; Waldron, 1960). Brown and Brandt (1970) instructed their subjects to ignore the masking noise and repeat vocal

utterances in a constant manner. Their subjects demonstrated small (3.7 dB) increases when presented with 107 dB SPL masking noise compared to typical increases of 10 to 13 dB cited in other studies. Siegel and Pick (1974) built maximizing, minimizing, and neutral conditions into their study by instructing subjects to attend to the feedback and compensate for changes in loudness, or to attend to their voice and maintain unaltered voice intensity. Subjects in the neutral condition received no instruction. They obtained significant but small sidetone amplification effects for all three instruction conditions with the greatest effect in the maximizing condition. They also reported their subjects did not comply with instructions to maintain constant voice intensity.

Instrumentation to quantify voice intensity in a simpler manner is now becoming available. This instrumentation is capable of extracting and displaying fundamental frequency and the amplitude envelope of a signal. In the studies reviewed, most researchers have used a graphic level recorder to measure the vocal output of their subjects (Amazi & Garber, 1982; Black, 1951; Charlip & Burk, 1969; Dreher & O'Neill, 1957; Garber et al., 1976; Lane et al., 1970; Ringel & Steer, 1963; Siegel & Kennard, 1984; Siegel et al., 1982; Waldron, 1960; Webster & Klump, 1962). This measuring technique is time-consuming and requires equipment not available in a typical audiology clinic.

Although the Lombard response is not standardized, researchers have concluded it is a phenomenon useful for research when variables are controlled that influence it.

Biasing Factors and Loudness Modulation Cues

Many researchers have drawn attention to the complexity of loudness studies. There is general agreement among researchers that the magnitude of the Lombard effect varies directly with the intensity of the masking noise (Charlip & Burk, 1969; Egan, 1971; Garber et al., 1976; Hanley & Steer, 1949; Waldron, 1960). The Lombard effect varies also with the frequency band of the masking noise (Black, 1950; Egan, 1971; Garber et al., 1976; Pickett, 1958) and whether it is presented binaurally or monaurally (Egan, 1971; Taylor, 1949; Waldron, 1960.)

Pickett (1958) reported that the intensity of the background noise is not the only factor that determines a talker's level of vocal effort, emphasizing that there are unknown factors which produce large individual differences among talkers. Over the years, researchers have attempted to identify and quantify the effect of the numerous unknown factors which influence an individual's vocal intensity.

Korn (1954) pointed out that adding acoustical damping materials to a room will reduce conversational noise by a factor of 1.6 greater than predicted by conventional formula

for environmental noise reduction. He attributed this greater-than-expected increase in noise reduction (conversational settings only) to the effect of "psychological feedback," but did not elaborate further. It is assumed his term "psychological feedback" refers to the tendency of talkers to find a balance between the need to be intelligible while maintaining social appropriateness (Carhart, 1970; Lane & Tranel, 1971). Social appropriateness may be described as "comfortableness" with meeting the demands of the situation. As such it may involve conservation of energy, the emotional state of the speakers, the communication requirements, and interpersonal dynamics. For example, Black (1949b) reported his subjects adjusted their own vocal intensity as the level of intensity of stimulus questions changed. Through interviews, it was found the subjects were aware they were changing vocal intensity. Black then instructed his subjects to keep their vocal intensity level constant despite changing intensity levels of stimulus questions and found they continued to change their intensity level with the changing stimulus intensity level.

Baird (1969) carried out a similar study and concluded that his subjects modulated their vocal loudness as a result of imitative modeling. From these studies it appears persons may adjust their vocal intensity level to match the intensity level of other talkers even when there is no

competition during the actual time they are talking.

When he developed the sone scale, Stevens (1955) found many factors affected loudness studies. He concluded that factors that affect loudness studies sometimes are so conflicting they all cannot be controlled in any one study.

Gardner (1966) carried out a series of experiments to demonstrate that numerous factors influence a talker's intensity level. Based on the large number of factors he identified and the wide variety in individual differences he observed, Gardner concluded that studies on talking levels will be meaningful only when all the conditions are described explicitly. He identified the following conditions as influencing voice intensity level in his study: ambient noise level, the distance between talker and listener, the nature of the communication task, the acoustics of the room, and the vocal habits and vocal capacities of the talkers. He found that subjects increased intensity levels by 4 dB when distances were increased from 39 inches to 12 feet. His subjects increased intensity when correct repetition by the listener was required and they demonstrated a wide variability in habitual talking levels. Gardner reported his subjects showed more uniformity (individual consistency) in vocal output when reading sentences than when participating in conversational exchanges. In addition, he compared "confidential" conversational exchanges with "declamatory" exchanges and

reported significant differences in intensity levels of the exchanges.

Many researchers have noted also a relationship between the intensity of the Lombard response and the communication task. Propositionality appears to play a role in enhancing a Lombard response. When a subject is talking to someone about something he will have a greater Lombard response than when talking to an empty room or into a tape recorder. Reading aloud or reciting meaningless lists of syllables or words minimizes the Lombard effect. Subjects who read spondee word lists produced less intense Lombard responses than when they read sentences (Dreher & O'Neill, 1957). Researchers concluded that a requirement for error-free communication will evoke a greater Lombard response.

Webster and Klump (1962) used additional talkers placed around their subjects as a competing noise source. They required error-free communication during their measured exchanges, that is, perfect repetition of the stimulus words. They concluded that an enhanced Lombard effect resulted when a premium is placed on intelligibility. Similarly, Lane et al. (1970) used a procedure that placed a premium on intelligible communication; they obtained an enhanced Lombard effect (slope 0.5) and an enhanced sidetone effect.

Kalikow and Stevens (1977) reported that a babble of voices produced by several speakers interferes with

intelligibility more than random nonspeech noise. The enhanced interference arises because the babble contains false speech cues, and because it increases the load on the attention and memory.

In their exhaustive review of the Lombard sign, Lane and Tranel (1971) concluded that the impetus for the adjusting response is determined more by the speaker's estimate of the listener's needs for intelligibility than the speaker's need to hear (monitor) himself.

Similarly, Garber et al. (1976) concluded from their series of experiments that the sidetone amplification and Lombard effects are related to speech intelligibility such that noises which maximally interfere with intelligibility induce large sidetone amplification and Lombard effects.

Black (1949a) began his series of investigations into factors which influence loudness modulation. He reported that under experimental conditions subjects responded with equally loud voice intensity in bright, dim, and dark environments. Interestingly, his subjects responded with disproportionately higher intensity to female voices compared to male voices. He postulated that the subjects were responding to the higher pitch of female voices.

Black (1951) investigated the observation that people tend to talk louder after exposure to noise. His subjects demonstrated a 9.0 dB temporary threshold shift in hearing following exposure to noise and increased their voice

intensity level 4.8 dB from baseline while reading aloud during the temporary hearing decrease. At three-minute-intervals, retests showed continuing resolution of the temporary shift in hearing threshold and a corresponding decrease in voice intensity level while reading aloud. Black concluded that the airborne component of the sidetone is important, but not the sole factor, in the feedback systems that contribute to setting the level of voice intensity. If a person does not judge the relative intensity of his own voice on the basis of auditory feedback alone, what then does he use? Lane et al. (1961) addressed this question and concluded that the judgment of the amount of vocal effort played a more crucial role in judging autophonic output than did judging sidetone loudness. Lane (1963) substantiated this claim by determining that persons who are prelingually deaf demonstrate an autophonic scale of voice intensity that parallels the autophonic scale for hearing persons devised by Lane et al. in 1961. His findings help to explain how a person who becomes deaf continues to modulate his vocal intensity level appropriately under certain conditions.

It is apparent there are many and varied categories of cues that individuals rely upon to modulate the intensity of their vocal output. Questions arise concerning how an individual makes such judgments--if, how or when sensory dynamics have an effect on the regulation of vocal intensity

levels.

The Role of Hearing in Speech

In the field of physics there is a term called bootstrapping which means the application of multiple models to explain a complex phenomenon (Capra, 1982). A complex model, for example, may be accepted and a simpler model may be employed conjointly; both models may explain what is happening at different levels of operation and under varying circumstances. The combination of the two models provides a clearer picture than either model used by itself. Speech scientists have recently been "bootstrapping", that is, combining seemingly contradictory models to explain the regulation of ongoing speech.

In an excellent review of the regulation of skilled voluntary performance, Greenwald (1970) outlined four basic nonverbal models of sensory feedback. (Verbal mediating mechanisms differ from nonverbal primarily by operating at higher levels of performance organization and will not be reviewed here.) In brief, two of these models, serial chaining and closed-loop, explain response selection using peripheral feedback from preceding correct and incorrect responses, respectively. Two other models, the ideo-motor and fractional anticipatory goal response mechanisms explain a response as directed by an anticipatory representation of

its own feedback. These models, at times, have been used to explain the regulation of speech.

The importance of auditory feedback (the closed-loop system) in speech learning is generally agreed upon (Amazi & Garber, 1982; Borden, 1979; Siegel et al., 1976) and is attested to by the difficulty with which congenitally deaf acquire speech (Elman, 1981).

For many years, Fairbank's (1954) explanation of the regulation of speech as a servo-system (closed-loop mechanism) brought the "peripheralists" stance into prominence. Mysak (1959) based a speech-error correction program on the servo-model. In current reviews, Zimmerman and Rettaliata (1981) and Zimmerman and Collins (1985) continued to support the significance of the role of auditory feedback in the regulation of speech. Theorists justify a closed-loop feedback system based in part on the observation that interference with the hearing of one's own speech causes the speaker to try to normalize any distortion. Studies that outline the disintegration of various aspects of speech following complete loss of hearing are used to support a closed-loop system. Kirk and Edgerton (1983) observed that the speech or voice characteristics of deaf persons differ considerably from those of normal hearing speakers and they attributed those differences to the loss of auditory feedback.

In recent years a number of researchers (who espouse a

central model for control of speech) have suggested the servo-mechanism may explain how one acquires proficiency in speech, but presents too many problems to explain completely the regulation of ongoing speech once it is established. These researchers have proposed a model similar to the ideo-motor mechanism that includes the generation of novel responses and takes into account the reaction-time problem inherent in the servo-system model. Borden (1979) reviewed ideo-motor models found in the literature under a variety of names. She reported Evarts used the term "internal feedback" to describe brain activity between the cerebrum and cerebellum with the cerebellum acting as comparator. "Central feedback" was a term suggested by Taub and Berman who state: "motor neurons do not have to be told they've fired, they know" (cited in Borden, 1979). From sports literature, Borden drew the terms "pre-selection," "corallary discharges," "efference copy," and "central monitoring of efference," all with similar emphasis on central regulating mechanisms. Essentially stated, these models propose a central monitoring of a copy of motor commands sent to the muscles; the brain does not have to wait for sensory feedback for comparison since it has its own preprogrammed image with which to compare. Pribram's discovery that the brain's motor centers are involved not only in movement but in thought processing (plans of action) preceding movement lends credence to these models (Ferguson,

1982).

The centralist's position is supported by studies that show processing time for sensory feedback is too lengthy for immediate correction of verbal output. The moment is passed before correction can take place. Higgins and Angel (1970) presented studies that showed subjects can recognize errors without sensory feedback. In addition they found error correction times for some well-learned motor tasks were shorter than the proprioceptive reaction times thus indicating central rather than peripheral monitoring. Auditory reaction time has a similar time differential.

Siegel, Fehst, Garber, and Pick (1980) reiterated that the articulation and timing aspects of skilled speech occur too rapidly to make much use of immediate auditory feedback. Pitch and intensity, which are more steady state dimensions of speech, continue to be susceptible to feedback monitoring.

In addition, arguments for central control are based on observing results following elimination of feedback. Goehl and Kaufman (1984) found that talkers who sustain a complete loss of sensory feedback, as in the case of adventitious deafness, may incur little effect upon their articulatory skills. They believed a servo-mechanism theory of speech control was not supported for articulatory regulation, but they did suggest other dimensions of speech such as voice quality, pitch, loudness, and timing were more susceptible

to auditory feedback.

In a later article, Kaufman and Goehl (1985) pointed out a problem in developing a theory for the regulation of speech. There is no way to test directly the role of auditory feedback in speech regulation. Instead, researchers can only observe what happens in natural situations or infer what system a subject uses on the basis of experimental manipulation.

Despite the use of oral anesthesia and masking producing massive feedback disruption, more than 80 percent of all consonants and all vowels were articulated correctly by subjects in Gammon, Smith, Daniloff, and Kim's study (1971). These results on temporary feedback deprivation led them to conclude that the articulatory system did not depend upon feedback to maintain its integrity.

In reference to loudness modulation, Lane and Tranel (1971) pointed out that a speaker may be disturbed by an unfavorable acoustic environment (or "harrassed by prying experimenters") and only then does he attend to his own voice. "The speaker need no more listen to himself while speaking than he need speak to himself while listening." They argued that the "public loop" is preemptive in controlling loudness modulation. Siegel and Pick (1974) grant the role of the public loop (social feedback) as one of the factors for intensity control but also refer to the importance of the auditory loop in their system. In their

view articulation is too fleeting to be under control of immediate feedback, but vocal intensity is highly responsive to feedback. They suggest a speaker has feedback available at all times, but may not attend to it until needed as in the case of conversing in a noisy environment.

Perkins (1984) appears to refer to a similar concept: speakers exercise the ability to regulate the timing of speech only when needed. Regarding the timing (fluency) aspect of speech, Perkins infers that speakers use automatic regulation of speech until some stimulus draws attention to their speech so that they must use voluntary control (controlled processing) to maintain speech appropriately. He asserts that in the case of fluency aberrations, the alerting stimuli are not known, but he surmises they may be some characteristic of the processing operation, or they may be kinesthetic, tactile, or auditory. If the alerting stimulus is auditory, it is probably available as feedback only after an utterance, not during the moment of speech.

An attempt to combine or "bootstrap" these models is currently seen in the literature. Elman (1981) described a hierarchical model that involves a master plan for an utterance that may be preprogrammed and that may use feedback to provide servo-mechanical control over execution of the command. Borden (1979) described a combined model as multi-level controlled, with auditory and tactile information operating as external feedback, proprioceptive

information operating as response feedback, and cerebrum, thalamic and cerebellar loops as internal feedback. Andrews et al. (1983) drew from Neilson's writings (cited in Andrews et al., 1983) to propose a merger of the stances of centralists and peripheralists which would allow both preprogrammed control and closed-loop feedback control to be operative. He proposed a hierarchical system with multiple levels of open- and closed-loop control. At one level, feedback may be continuous and provide correction, at another level, feedback may provide evaluation and may be received after the speaking moment has passed.

Hutchinson & Putnam (1974) based a similar concept of an open-loop and feedback dependent motor control system on their studies of sensory-deprived speech. Specifically, they identified dimensions of temporal sequencing of speech as being under open-loop control.

The complex model of speech regulation that is emerging employs central imaging of the motor act of speech preceding production. When the attention is drawn to speech, additional options for regulation are provided by sensory feedback, with some aspects of speech, such as intensity, being more responsive to feedback than others.

Replacement of a Damaged Sensory System

The thrust of the preceding discussion takes on

direction as the next problem is considered. It has been documented that loss of hearing impacts greatly on communication ability. One particularly disconcerting outcome of profound hearing loss is a fluctuating ability to regulate loudness level. At times deaf individuals do demonstrate appropriate loudness modulation. It is theorized they accomplish this by relying on central monitoring using a preprogrammed "image of energy output for loudness." They base their loudness regulation, in part, on the amount of effort expended in talking rather than on the ongoing feedback of hearing themselves talk. On occasion, this system fails the deaf individual. When he finds himself in a very noisy or reverberant environment, he lacks the auditory feedback that is then necessary to make adjustments in vocal output. When expressing emotional involvement, he needs the fine grading skills based on auditory feedback necessary to change his intensity level appropriately.

Scientists have long held the idea of replacing the lost function of hearing in those with sensorineural deafness. In the past 10 years, over 100 years of study has been brought to fruition by the development of a prosthetic device designed to be a substitute neural interface with the auditory nerve, replacing the function of the damaged hair cells of the inner ear.

A cochlear implant is a prosthesis designed to aid

persons with a sensorineural deafness to hear sounds again. In sensorineural deafness, the functioning of the hair cells in the cochlea is impaired; yet many of the auditory nerve fibers remain intact which allows sound to be transmitted if a method of stimulating them can be achieved.

To reach this point of substituting a prosthetic device for a damaged neural-sensory system of hearing, investigators needed first to understand the role of the cochlea in transmitting sound.

Transmission of Sound in the Normal Ear

In the 1800's, Herman von Helmholtz investigated the sympathetic vibration of the basilar membrane and identified the organ of Corti as involved in sound transmission. An important concept was established in the 1930's when Wever and Bray determined that the function of the cochlea was to transduce mechanical sound energy into electrical impulses (Balkany, 1983), and von Békésy in the 1950's developed the place pitch theory of movement of the basilar membrane. Place pitch theory hypothesizes when sound is applied to the cochlea, the basilar membrane vibrates; the largest amplitude of vibration occurs at the particular place on the basilar membrane which is mechanically tuned to the frequency of the particular sound (Loeb, 1985). The place pitch theory underlies, in part, the design of most

multi-channel cochlear implants. As investigators have broadened their observations into theories of hearing, the design for building a sensory prosthesis has emerged.

The pathway of sound to the auditory nerve in the normal ear can be described as follows: sound vibration is transmitted mechanically through the ossicles of the middle ear to the oval window where the vibration is relayed to the fluid-filled interior of the cochlear, in turn stimulating the basilar membrane which runs the length of the cochlea. Hair cells, arranged in rows along the basilar membrane, transduce the mechanical motion (vibration) of the basilar membrane into an electrical signal which stimulates the end organs of the auditory nerve producing neural discharge patterns. These "evoked potentials" travel the neural auditory pathway to the brain to be interpreted as sound (Loeb, 1985).

The role of the hair cell in encoding the sound signal in the auditory nerve continues to be investigated. Intensity encoding by the hair cells is of interest to this paper; pitch encoding will not be discussed. Viemeister (1974) summarized a commonly accepted theory of intensity encoding in terms of the number or spatial pattern of active primary fibers that are fired. A multiple-fiber hypothesis is advanced over a single-fiber theory based on the discharge rates of a single fiber. It is known that a primary fiber saturates at intensities 30-50 dB above

threshold. Thus, a single fiber would not be capable of detecting small changes in intensity above 50 dB, and yet the known range of sound discrimination in the human ear is over 100 dB. Therefore, it is hypothesized that intensity is encoded by a spread of excitation along the cochlear partition. Specifically, as intensity increases more fibers are activated at each end of the active array of fibers. Loeb (1985) summarized: "the loudness of the sound perceived depends roughly on the number of nerve fibers activated and their rates of firing."

Electrical Stimulation of the Ear

The earliest noted experiments in stimulating the ear electrically were performed by Alessandro Volta. The story is told that Volta, in 1790, applied electrical current from his newly developed electrolytic cell to metal rods placed in his own ears and promptly lost consciousness. Later, he described the auditory sensation: "I heard a sound like thick boiling soup" (Hough et al., 1982). He apparently chose not to repeat the experiment (Balkany, 1983; Parkins & Anderson, 1983; Simmons, 1966).

In the early 1930's a number of studies were reported involving subjects with profound hearing losses who experienced auditory sensations following electrical stimulation of their cochleas (Balkany, 1983; Simmons,

1966). Substantial progress in the field occurred in 1957 when Djouino and Eyries in France bypassed the hair cell function and stimulated directly the auditory nerve fibers of two deaf patients. Electrodes were successfully placed in their ears for a term of several years (Owens, 1984). In the United States, Simmons in 1966 reported the first psychophysical data from electrical stimulation of the auditory nerve. Simultaneously, in the 1960's, House developed a single-channel scala tympani electrode system and Michelson developed a multi-channel electrode system (Miller, 1985). In the 1970's, significant developments were presented by Eddington in Utah, Hochmair and colleagues in Austria, and Clark and associates in Australia ("Cochlear Implant," 1985; Miller, 1985). In early 1985 the Federal Drug Administration approved the House single-channel device for implantation in persons with sensori-neural deafness (Loeb, 1985). Later that year, the Nucleus 22-channel device was approved for implantation. Advances in surgical techniques, miniaturization of electronic circuitry, and increased understanding of the operation of the ear have led to the emerging of the era of the electronic cochlear prosthesis (Millar et al., 1984).

The Cochlear Implant

Many types of cochlear implants are being developed.

They all have four features in common: 1) a microphone for picking up the sound, 2) a micro-electronic processor for converting sound into electrical signal, 3) a transmission system, and 4) the electrode(s) that deliver the electrical stimuli to the fibers of the auditory nerve in one or more places (Loeb, 1985; Owens, 1984).

The transmission system in a cochlear implant includes an externally-placed transmitter which sends the signals received from the microphone across the skin barrier to a receiver coil, surgically embedded in the mastoid process. The signal proceeds by cable to the electrodes. The electrode array in the various designs can be either one channel of information or several channels delivered separately to different electrodes (Staller, 1985). In many instances the electrode is placed into the cochlea or an extra-cochlear electrode can be placed at the round window. The number of electrodes that can be used is limited at present. Because the cochlea is fluid filled, electrical stimulation at one site within the cochlea spreads to other areas of the cochlea in a radially symmetrical pattern. A disrupting noise sensation arises as the excitation reaches more distant areas of the cochlea. The electrode array of multi-channel devices uses either low-intensity monopolar stimulation or bipolar stimulation to confine the excessive spread of stimulation within the cochlea. To prevent the current from spreading radially throughout the cochlea and

interfering with stimulation at other electrode sites, monopolar contacts placed at a distance from one another, must be used at low stimulation rates. In contrast, bipolar contacts tend to produce a more localized pattern of excitation which allows higher stimulation rates and more electrodes to be used (Loeb, 1985).

Processor Strategies

Atal (1983) provided background information that is helpful in understanding speech encoding with a cochlear prosthesis. His model explains speech as a type of code used between persons to transmit ideas. A special attribute of this code is robustness which allows for accurate transmission even when an interference causes a distortion or masking of the code. The robustness is built into the code through redundant encoding of the bits of the message. When the natural acoustic channels used for receiving speech are damaged an electrically-stimulated, digital channel may be substituted. The current state of technology severely limits the amount of information a digital channel can carry compared to the capacity of the acoustic channel in the human ear. To save channel capacity for only the most important and essential message-carrying bits of information, redundancy in the speech code must be eliminated. The aim of speech coding using a digital channel is to determine and then extract only the essential

information needed in order to transmit the message.

In the design of their prostheses, each research center applies different speech processing strategies to transform the redundant speech signal into simpler coded signals that can be relayed to the comparatively crude electrode interfacing the nerve fibers (Millar et al., 1984). Pfingst (1985) explained that the speech waveform must be simplified and reduced. The partially damaged ear has limited capabilities for information transfer by electrical stimulation compared to the capabilities for information transfer in the normal ear.

Three general types of processor strategies are in use for encoding. One type employs a feature extraction approach which provides "pulse trains" (pulsatile stimuli) that vary in rate, width, and amplitude to correspond to various features of the input signal (Mecklenburg & Brimacombe, 1985; Pfingst, 1985; Staller, 1985). Only the features deemed important in speech perception are extracted and coded. All other information is excluded to avoid contaminating the useful information (Millar et al., 1984).

The second approach is an attempt to mimic the "normal" physiological response characteristics of the auditory system (Miller & Pfingst, 1984). This strategy uses analog waveforms (direct electrical representation) of the speech signal that have been filtered, compressed, and adjusted in relative amplitude (Pfingst, 1985; Staller, 1985).

A third strategy (the House device) amplifies the speech signal and uses a bandpass between 350-Hz and 2.5K-Hz, then "uses a 16K-Hz sinusoidal carrier that is amplitude modulated in relation to analog environmental sounds" (Pfungst, 1985). As Mecklenburg and Brimacombe (1984) explained it:

The filter bank approach applies gains and compression to the input acoustic signal, divides the frequency spectrum received into varying numbers of bandwidths (filter banks) and presents them as an electrical analog to different places in the cochlea.

The three approaches are not mutually exclusive; various prostheses available today combine some components of each strategy (Miller & Pfingst, 1984).

The timing, intensity and frequency components of the speech processor must be programmed for each individual. The programming of intensity information, germane to this paper, is discussed in more detail. Intensity is programmed as a function of the amplitude of the stimulus current. Thresholds for detection and upper limits of comfortable loudness are determined for each individual and the input is amplified or limited appropriately (Pfungst, 1984; Tyler et al., 1984).

With appropriate compression of the signal, loudness is transmitted in nearly a normal manner (Millar et al., 1984). The resultant threshold contour and dynamic range for each individual depends on the remaining nerve fibers and on the

spacing and location of the electrodes (Pfungst, 1984; Pfingst, Burnett, & Sutton, 1983).

Muller (1983) reported that the full dynamic range from threshold to uncomfortably loud is from 8 to 20 dB of electric current. Edgerton (1985) elaborated on that data, reporting that the dynamic range is greater for frequencies below 300-Hz (approximately a 20 dB range). The dynamic range decreases for mid-frequencies (approximately an 11 dB range) and increases again for high frequencies. The result is a comparatively rapid increase in the perception of loudness with small increments of electrical current. Close to a doubling in loudness is perceived for each 4 dB increase in stimulus level. Hochmair and Hochmair-Desoyer (1983) explained that the difference limen for electric current is small, thus this range is similar to that of a normal hearing person. Pfingst et al. (1983) explained further that the functionality of this limited dynamic range depends on the number of steps in intensity that can be discriminated. Psychophysical testing with a number of persons using cochlear implants reveals that the minimal discernible difference in loudness appreciation is 2 dB (varying from 0.07 to 7.00 dB). These results for intensity discrimination with electrical stimulation lie within the discrimination response range of the normal ear (Balkany, 1983; Pfingst et al., 1983).

Two Second Generation Cochlear Implants

Two prostheses are of special interest to this paper; three subjects in the study were implanted with a Nucleus 22-channel prosthesis and two subjects received a 3-M Corporation extra cochlear device. More specific descriptions of these two advance design (second generation) implants follows.

The Nucleus 22-channel cochlear implant was developed by Nucleus Limited and is based upon research by Greame Clark and colleagues at the University of Melbourne, Australia. The implant consists of a speech processor (worn on the body), an external headset with microphone and transmitting aid, and an implanted receiver-stimulator. The signal is sent to a 22-electrode array which has been inserted via the round window approximately 2.5 mm into the cochlea ("Cochlear Implant," 1985).

The speech processor estimates the amplitude, the fundamental frequency and the second formant of the incoming sound stimulus and passes it through an analog-to-digital converter (Mecklenburg & Brimacombe, 1984). The processor codes specifically extracted features of speech rather than using a filter bank method.

The receiver-stimulator receives the externally coded stimulus information and generates charge-balanced, constant current, biphasic stimulus pulses on the selected electrode pairs. The rate of stimulation at the electrode represents

the fundamental frequency of the input signal. The place of stimulation, that is, the specific electrode along the basilar membrane selected for stimulation, represents the second formant of the signal. For example, a high frequency sound will stimulate an electrode located toward the basal area of the cochlea while a low frequency sound will stimulate a more apically situated electrode (Mecklenburg & Brimacombe, 1984). A multi-channel implant such as the Nucleus model is more appropriate for persons who have a well-distributed array of surviving auditory nerve fibers.

The second type of cochlear implant is the 3-M Corporation extra-cochlear device. As described by Staller (1984), the extra cochlear device was developed by a Viennese group headed by Hochmair, Hochmair-Desoyer, and Burian and is manufactured by 3-M Corporation, St. Paul, Minnesota. It is a single channel prosthesis consisting of a speech processor worn on the body and an external headset with microphone in an ear-mold assembly. A postauricular transcutaneous transmitter and an implanted internal receiver deliver a coded input to an active ball electrode that rests on the promontory or in the round window niche.

The coding strategy used involves a frequency-compensated analog of the speech signal. The acoustic input is converted to an electric analog by the microphone. The signal is preamplified and compressed and filtered by four bandpass filters to equalize the loudness

energy across the sound spectrum and then delivered to the electrode. The processor's output is individually set to prevent exceeding the implantee's comfortable loudness level. The implantee may adjust the volume between zero and the maximum output.

The extra cochlear implant provides all the advantages of a single channel cochlear implant. Because it is noninvasive it may be the prosthesis of choice for patients with residual hearing that should be preserved, for those who have a restricted population of auditory nerve fibers remaining, or for patients who cannot anatomically accept an inter-cochlear device.

Sound Perception With a Cochlear Implant

The sound of electrical stimulation differs greatly from the sound of acoustical stimulation according to implantees. They do not hear sounds as they once did, but must learn to use the limited information they receive from the implant. Loeb (1985) described the sensation as a complex noise containing minimal pitch cues, but good cues for rhythm and loudness of speech.

Thielemeir, Brimacombe, and Eisenberg (1982) reported implant users describe the sound as "mechanical" or having a "static-like quality," "scratchy," "tinny," or "like the buzz of an electric drill." At first, everything sounds the same to a new prosthesis user. As implant users adjust to

listening to electrical stimulation, they develop critical listening skills. Differences in sound begin emerging, the "beats" of connected speech can be heard, and differences in sound can be ranked (Maddox & Porter, 1983; Thielemeir et al., 1982). Background noise is especially bothersome initially, but as sound takes on specific qualities, the implant user learns to attend to the signal and ignore the background noise. They report that the sound of their own voice is especially troublesome to them. Over time, they adapt and learn to use the information received from hearing their own voice.

Millar et al. (1984) adds a fifth component to the cochlear implant system: the perceptual system of the implantee. The number of neural elements remaining in the cochlea of a deaf person is highly variable and greatly influences how much information can be transmitted. Other factors influence how a person uses the limited information. Motivation, cognitive style, and the flexibility of hearing strategies developed prior to deafness influence highly the eventual level of use of the implant.

Effect of Cochlear Implant Use Upon Speech Regulation

Subjective reports in the literature indicate that cochlear implant users demonstrate improvement in loudness control (Hough et al., 1982; House, 1978; Thielemeir et al., 1982). One study has appeared in the literature that

employs actual measurement of change in vocal output following implantation with a cochlear device. Kirk and Edgerton (1983) subjectively identified four implant users as demonstrating vocal changes following implantation. To validate their subjective assessment, they measured three dimensions of vocal production and compared the results to five normal hearing control subjects. Recorded speech samples of a read passage were collected under two conditions: implant on and implant off. Fundamental frequencies for each subject were determined, the ranges of vocal intensity used were determined, and the mean durational measures of phrases were determined. With implants on, the subjects produced fundamental frequencies and variability in intensity levels that were more like the responses of the five normal hearing control subjects for the same task. Their subjects demonstrated prolongation of sentences and pauses more consistent with deaf speakers in both implant off and implant on conditions. They differed significantly from the normal hearing controls in this aspect of vocal output.

Predictions for Success

As mentioned earlier, the individual response to electrical stimulation depends upon many factors. Dominant among these factors are the number of nerve fibers remaining

and the number and placement of electrodes in relation to the remaining nerve fibers. Wide differences exist between the many research centers in types of implants used, the amount of rehabilitation provided, and the conditions under which tests are carried out. Thus generalizing from the data on cochlear implant use to specific predictions of an individual's response to electrical stimulation is not possible at present, although inferences may be drawn regarding useful aspects of implant systems (Millar et al., 1984). The variability in rehabilitation success across all implant systems is great, making comparison and prediction difficult (Loeb, 1985; Pfingst, 1985). A few "star" patients demonstrate ability to perceive connected speech without the aid of lipreading; the vast majority of implant users benefit to a lesser degree (Miller & Pfingst, 1984). Millar et al. (1984) ascribed highly successful use of a cochlear implant to factors related to the individual implantee rather than to the design of the speech processor alone. Repeatedly, researchers emphasized the importance of the number of excitable peripheral nerve fibers available in determining successful use. In addition, Millar et al. (1984) singled out cognitive style as a significant factor in successful use of an implant. Blesser (cited in Millar et al., 1984) delineated the more successful "synthetic generalist" as one who will guess the sense of what is being said, as compared to the less successful "analyst" who

concentrates on the discrimination of sound elements. Millar et al. (1984) reported they noted informally that their successful implantees used a cognitive style that "attempts to grasp at new cues and use them with confidence."

At present, it appears studies of performance of cochlear implant subjects must take individual differences into careful consideration. In addition there is little objective data on how wearing a cochlear implant impacts upon the dimensions of speech, especially the dimension of loudness modulation.

CHAPTER III

METHODS

General Plan

A review of the literature suggests that when speakers have normal hearing, the intensity of their vocal output is related directly to the intensity of the background noise (Waldron, 1960). In the present study, this relation was quantified by measuring the intensity of the vocal output of five listeners with normal hearing while different levels of background noise were presented in counterbalanced order. The experiment then was repeated for each of five cochlear-implant patients under two conditions. For one condition, the cochlear implant was turned on and adjusted appropriately. For a second experimental condition, the implant system was turned off. Comparison of data from the two subject groups was used to address the experimental questions.

Subjects

The five experimental subjects chosen for this study were participants in a second-generation cochlear-implant

study at Good Samaritan Hospital and Medical Center, Portland, Oregon. Criteria for inclusion in the implant study included 1) profound hearing loss, 2) functional speech and language performance (deafness sustained post-lingually), 3) a surviving population of auditory nerve fibers capable of responding to electrical stimulation as determined by pre-operative testing, 4) general good health as determined by a pre-operative physical examination, 5) 18 years of age or older, and 6) little or no benefit from a hearing aid in the ear to be implanted. Table I provides a summary of each subject's history. Subjects 2 and 3 wore hearing aids in the non-implanted ear. These subjects were instructed to turn their hearing aids off during the study.

The candidates received one of two investigational second-generation cochlear implants. Subjects 1, 2, and 4 received a multi-channel prosthesis with speech processor from Nucleus Corporation of Melbourne, Australia. Subjects 3 and 5 were fitted with a single-channel implant designed to drive an extracochlear pair of electrodes placed on the round window of the cochlea. This implant was developed by Hochmair and associates of Austria and was available from the 3-M Corporation, St. Paul, Minnesota. A battery of psychoacoustic and electrophysiologic tests including an exploratory tympanotomy and diagnostic electrical stimulation at the round window was used to estimate the number and location of nerve fibers remaining. The

TABLE I

BIOGRAPHICAL DATA FOR
EXPERIMENTAL SUBJECTS

SUB- JECT	GEN- DER	AGE YEARS	EDUCA- TION YEARS	TIME DEAF YEARS	ETIOLOGY OF DEAFNESS
<hr/>					
1	M	50	12	1	PERILYMPH FISTULA DUE TO HEAD TRAUMA
2	M	51	16	2*	PERILYMPH FISTULA DUE TO HEAD TRAUMA
3	F	64	19	5*	PROGRESSIVE SENSORI- NEURAL HEARING LOSS
4	F	60	14	2	MENINGITIS
5	M	70	12	10	PROGRESSIVE SENSORI- NEURAL HEARING LOSS
* WITH HEARING AID					
<hr/>					

neuro-otologist and the audiologists determined the appropriate implant for each candidate based on the pre-operative results.

The audiologist and the speech-language pathologist on the cochlear implant team at Good Samaritan Hospital and Medical Center directed the training phase of rehabilitation for the cochlear implant patients. Appendix A provides an overview of the rehabilitation program. The subjects had at least four months of experience with electrical stimulation before participating in this study. Their hearing level before implantation and after six months of stimulation is displayed in Table II.

The five control subjects chosen were matched to the experimental subjects with respect to age, gender, and education (as an index of socio-economic level). Control subjects were solicited from among friends of the experimental subjects and from various church groups. These control subjects had hearing levels within 5 dB of the predicted socio-acusic curves for their age (United States Department of Health, Education, and Welfare, 1980). Table III provides biographical data and an audiometric profile for each control subject. Each of the cochlear implant subjects and the normal hearing subjects signed consent forms to serve as human subjects as shown in Appendix B.

TABLE II

PRE AND POST IMPLANT
SOUND-FIELD TESTING IN DB

SUB- JECT	IM- PLANT TYPE	4 FREQUENCY		SDT		MCL		MONTHS IMPLANTED PRIOR TO LOUDNESS STUDY
		PTA						
		PRE- OP	6-MO POST	PRE- OP	6-MO POST	PRE- OP	6-MO POST	
1	NUC	NR	25	70*	30	NR	60	10
2	NUC	NR (62)**	17	NR (55)**	15	90*	60	10
3	3-M	52 (37)**	22	45 (40)**	20	80 (80)**	45	4
4	NUC	NR	23	NR	15	NR	60	10
5	3-M	NR	40	85*	25	NR	55	6

PTA - PURE-TONE AVERAGE

SDT - SOUND DETECTION THRESHOLD

MCL - MOST COMFORTABLE LEVEL

* VIBROTACTILE RESPONSE

** HEARING AID IN NON-IMPLANTED EAR

TABLE III

BIOGRAPHICAL DATA AND HEARING RESPONSES FOR CONTROL SUBJECTS

BIOGRAPHICAL DATA				PURE-TONE HEARING LEVEL (DB)							
SUB- JECT	GEN- DER	AGE YEARS	EDUCA- TION YEARS	FREQUENCY IN HERTZ							
				500		1000		2000		4000	
				R	L	R	L	R	L	R	L
A	M	49	12	0	0	0	10	10	15	0	5
B	M	57	16	10	0	15	10	20	15	40	25
C	F	68	18	10	20	10	20	10	25	0	20
D	F	63	15	30	25	25	25	25	30	10	5
E	M	68	12	20	25	15	20	20	25	40	45

Procedures

For this study, each subject participated in a single session that lasted approximately 25 minutes. None of the subjects was told the nature of the study. They were informed that their voice would be recorded as they read aloud and answered questions.

As illustrated in Figure 1, the subject sat in a reverberant room, facing the investigator at a distance of 1 m. This arrangement was designed to simulate a typical conversational setting. The subject's chair was adjusted so that an omni-directional microphone was 45.7 cm from the top of the subject's head. An acoustically shielded directional microphone was adjusted to a position 2.5 cm from the subject's lips. These microphones are depicted in Figure 2.

The subject was instructed to sit comfortably back in the chair and to maintain a steady head position, equi-distant from the two microphones. In preparation for the actual experimental condition, the subject was instructed to read aloud a joke and was told to remember the elements of this story for re-telling during the study. A practice reading of a standardized speech passage was recorded in the quiet condition to acquaint the subject with the procedures. The subject was told "at times during the tasks you may hear some noise in the background. I need to hear you clearly

Figure 1. Background noise composed of the incoherent babble of sixteen talkers is delivered to the subject at specified intensity levels via four loudspeakers while the subject talks to the investigator.

Figure 2. Block diagram of instrumentation used to record speech. Speech elicited from the subject was recorded on one channel and background noise from the loudspeakers was recorded on a second channel.

during the tasks so talk directly to me. From now on I'll communicate with written instructions." The cochlear-implant subjects were instructed to turn their prostheses off; in addition, the two implantees who wore hearing aids were instructed to turn their instruments off for the remainder of the study.

During the experimental conditions, the investigator remained silent to ensure that cues for vocal intensity would not be provided inadvertently. Each subject followed written instructions that elicited 8 to 10 minutes of talking during four different speech tasks. The vocal output was recorded on magnetic tape for analysis later.

During the experiment, a second investigator controlled the play, pause, and stop function on the two cassette reproducers. He adjusted the level of background noise delivered from the four loudspeakers to the subject. The protocol of the study determined when the background noise was set at 0 dB SPL, 70 dB SPL or 90 dB SPL. An example of the experimental sequence presented to one subject is provided in Table IV. The cochlear-implant subjects repeated the entire sequence of speech tasks a second time with their implants turned on, but with background noise levels presented in a different order. The tape-recorded speech output of all subjects under all conditions was analyzed subsequently for relative intensity changes using a digital storage oscilloscope.

TABLE IV

ORDER OF NOISE PRESENTATION

SPEECH TASK	ORDER OF NOISE PRESENTATION			DURATION OF TASK
ANSWER CLOSED QUESTIONS	QUIET	70-DB	90-DB	3 MIN
READ A PARAGRAPH	70-DB	90-DB	QUIET	1 MIN
TELL A STORY	90-DB	QUIET	70-DB	3 MIN
ANSWER OPEN QUESTIONS	QUIET	90-DB	70-DB	6 MIN

Speech Task and Materials

Previous studies have shown that the communication task influences the Lombard response. It was deemed desirable to elicit an enhanced Lombard response in order to produce unequivocal results. In constructing the speech milieu, emphasis was placed on requiring the subject to convey responses that were intelligible to the listener. Meaningful stimulus material was used. The subject talked to the investigator. Four speech samples were elicited from each subject; two samples were designed as closed message sets and two samples were open message sets. The order of presentation of the speech tasks required increasing attention to the content of speech output. This was done to distract attention from the volitional control of speech and to tap into automatic control of intensity modulation. The speech tasks were presented on cue cards typed in large print for easy reading.

Each subject was instructed to answer six closed questions from the printed cue cards held by one investigator. Refer to Appendix C-1 for the questions asked. The subject then read aloud the standardized speech sample "The Grandfather Passage," which is included in Appendix C-2 (Darley, 1975). This was followed by a typed request to retell the joke practiced earlier. A copy of the joke is in

Appendix C-3. Finally, the subject answered three open-ended questions presented on written cue cards. These questions are included in Appendix C-4.

Instrumentation

In preparation for the experimental study, the recorded output of four talkers reading simultaneously ("Four Talker Babble," Auditec of St. Louis) was dubbed out-of-phase onto four tracks of two audio cassettes. Each cassette then represented eight talkers. The "babble" of many talkers was used as background noise to provide maximum interference with intelligibility and to simulate natural conditions of noise interference.

Figure 1 provides a diagram of the experimental environment for presenting noise to the subject. One loudspeaker was placed near each corner of a 3.72 m by 3.95 m reverberant room. A manikin (Knowles Electronics Corporation, "KEMAR") was placed at the bisection of two diagonal lines drawn from opposite corners of the room between each pair of loudspeakers. Each of the two "Four Talker Babble" audio cassettes was played on a two-channel stereo magnetic cassette reproducer (Sony TC-FX25). A two-channel attenuator (Daven Precision T-532-G) was inserted between the line output of each tape reproducer and the line input of each two-channel power amplifier (Pioneer SX-400).

The babble was delivered out of phase to each of the loudspeakers. First, the acoustic output of each loudspeaker operating in isolation was calibrated with a sound-level meter (Bruel & Kjaer, Type 2230) placed at the head of KEMAR. Then the babble was delivered to all four loudspeakers simultaneously and the sound pressure level produced was measured again with the sound-level meter. The attenuators were set to deliver background noise at levels equivalent to 70 dB SPL and 90 dB SPL. Results from other studies indicate that background noise of 70 dB SPL and 90 dB SPL will evoke Lombard responses. The final effect was incoherent babble from sixteen talkers delivered at a specified intensity level to a subject's head.

Figure 2 is a block diagram of instrumentation used to record the speech elicited from the subjects. An omni-directional microphone (Audio Technica AT8-03A) was adjusted to a position 45 cm from the top of each subject's head. The output from the omni-directional microphone was fed to the right channel of a reel-to-reel magnetic tape recorder (Sony TC-640). This was designated as the noise channel. An acoustically shielded directional microphone (Audio Technica AT-15A) was mounted on a boom and adjusted to 2.5 cm from the subject's lips. The output from this microphone was fed to the left channel of the tape recorder. This was designated as the speech channel. The two microphones were matched with respect to frequency response

characteristics and sensitivity.

Prior to the experimental sessions, babble was delivered to the four loudspeakers simultaneously with an investigator seated in the experimental chair. The sound pressure level produced was measured at the omni-directional microphone, at the investigator's head, and at the directional microphone. With the attenuators set for 90 dB SPL, measurements at these three positions ranged from 90.0 to 90.6 dB SPL. During these measurements the noise also was recorded through the two experimental microphones. These recordings were used later as references for the vocal intensity measurements read from the oscilloscope. All noise measurements were repeated and recorded at the end of the experimental sessions. With the attenuators set again for 90 dB SPL, the measurements at the three positions ranged from 90.3 to 91.8 dB SPL.

Obvious problems are created when attempting to measure a speech signal in a background noise. Typically, an experimental study for measuring the Lombard effect would present the noise to the talker via earphones in order to record the talker's output separately from the noise. This type of experimental design was not possible for subjects with cochlear implants. The design of the cochlear implant microphone pickup limits the delivery of background noise to sound-field presentation. Moreover, sound-field mode of delivery was desirable to simulate, as closely as possible, the noise conditions encountered naturally.

Several steps were taken to reduce noise contamination of the speech channel. The design of the acoustically shielded, directional microphone eliminated considerable pick-up of background noise. To provide an acoustical advantage and to improve the message-to-competition ratio, the microphone was placed in close proximity (2.5 cm) to the subject's lips. In addition, the differential-amplifier function on the oscilloscope was used to cancel some of the remaining noise recorded on the speech channel.

The recorded speech samples were analyzed for intensity using a digital storage oscilloscope (Tektronix, model 468). The output of the left (speech) channel from the tape-recorded samples was fed into channel 1 of the oscilloscope. The output of the right (noise) channel from the tape-recorded speech samples was fed into channel 2 of the oscilloscope. Channel 1 and channel 2 on the oscilloscope were added and inverted. This procedure cancelled a portion of the noise that was contaminating the speech channel.

Waveform readings were read at a time setting of 0.1 ms/division and at an amplitude setting of 0.5 volts/division. The waveform of each word chosen for measurement was identified on the display screen and placed in the save storage mode. Voltage measurement values were obtained using the volts-cursor function and were read from the four digit, LED display. In addition, the amplitude of

the waveform of the background noise was sampled periodically and corresponding voltage measurements of the noise also were obtained.

Data Measurement and Analysis

Due to the large volume of potential data points, analysis was restricted but in all cases included at least 60 percent of the stressed syllables of the words in each sample. An exact script was written of the speech elicited from each subject. The tapes of speech samples were reviewed and all stressed syllables were identified and counted. At least 60 percent of the stressed syllables from each of the four speech tasks then were analyzed for vocal intensity using the oscilloscope. Measurement of the waveform energy was accomplished by identifying initially a word to be analyzed on the display screen. At that point signal acquisition was halted, the waveform was stored and remained displayed indefinitely allowing precise measurement. Pressing a volts-cursor function button caused two moveable horizontal lines to appear on the display screen. These were positioned to mark the peak-to-peak vertical deflection (areas of greatest amplitude) of the waveform of the chosen stressed syllable. In this manner a voltage difference measurement for that particular syllable was obtained. The voltage measurement was read from a four digit LED display.

For any one speech task, a minimum of 60 percent and up to 100 percent of the stressed syllables was analyzed. Reading a minimum of 60 percent of the potential stressed syllables allowed elimination of words that were difficult to identify or difficult to read and made the analysis project more manageable.

Two problems with the data analysis arose: 1) developing waveform reading skill and establishing reading consistency and 2) measuring speech samples "buried in noise." The following procedures were established to solve these problems.

1) In order to achieve expertise in identifying waveforms for specific words, photographs were taken of words in isolation to serve as reference templates. Sample photographs of these waveforms are displayed in Appendix D. The phonetic features of known words were correlated with their visible acoustic feature patterns as displayed on the oscilloscope. Skill was developed for identifying words in context by examining the patterns of features of words in isolation.

Data analysis took several weeks to complete due to the large number of data points to be read. To avoid daily fluctuation in reading, criteria for consistent measurement of the waveform using the volts-cursor function were established: The bulk of the energy of a syllable was bracketed with the cursors and "outriding" spikes were

omitted if they represented less than one-fourth of the syllable energy. A sample is shown in Appendix D. The two investigators compared speech waveform reading measurement techniques and matched to within 0.3 dB.

2) Some speech samples were difficult to identify or read because they were "buried in noise." Voltage readings were obtained for all normal hearing subjects and for the cochlear-implant subjects who demonstrated a Lombard effect. It was difficult to identify stressed syllables under the 90 dB SPL noise condition for those subjects who demonstrated minimal or no Lombard response. The speech waveforms were obliterated by the noise waveforms of the same or greater intensity. Several approaches to these problems were made.

a) Some speech samples were judged subjectively as demonstrating a minimal Lombard effect. These were tentatively identified, signal acquisition was halted, and the display frozen in the save storage mode. The Tektronix 485 oscilloscope has the capacity to reduce the relative amplitude of the stored signals by increasing the volts per division displayed. The volts per division switch setting was changed to 1 or 2 volts per division so that the noise waveforms (and also the speech waveforms) were reduced dramatically in size. This allowed a gestalt of the visual display. From this vantage point, patterns of syllables emerged that could not be identified previously. Once they were

identified, they were magnified to the original reference level (0.5mv/div) for consistent measurement.

b) After listening to the audio tape, some speech samples were judged subjectively as demonstrating no Lombard effect. In fact, most of these words were masked to the point of being unintelligible. This was especially true of some habitually soft-speaking subjects in the implant-off condition. If the procedure for identifying words with minimal Lombard effect was unsuccessful, then the average intensity values of the syllables obtained in the 70 dB SPL condition for that same speech task were assigned to the 90 dB SPL condition.

Inter-rater reliability of intensity measurements was assessed by asking the second investigator to re-analyze the data from randomly selected sections of the tapes. The average difference in intensity calculated by the two raters was less than 1.0 dB.

Descriptive statistical measures were applied to the data points obtained under the various conditions for each subject. Means and standard deviations were calculated and can be found in Appendix E. The ratio of change in intensity between talking in quiet and talking in 70 dB SPL noise was computed for each subject across all four speech tasks. The computation was repeated to determine the ratio of change in intensity comparing talking in quiet to talking in 90 dB SPL

noise. The derived voltage ratios then were converted to decibels using a conversion table and are available in Appendix E.

CHAPTER IV

RESULTS AND DISCUSSION

Results

The purpose of this study was to investigate the hypothesis that persons who are deaf and who have received cochlear prostheses will demonstrate intensity regulation of their vocal output that is more appropriate with their implant turned on than when their implant is turned off. The Lombard response was chosen to serve as the dependent variable to test this hypothesis. Preliminary to eliciting a Lombard response from the experimental subjects, it was expedient to determine that the test environment indeed would elicit a Lombard response in normal hearing persons. Five control subjects matched with the experimental subjects for age, gender, and educational level participated in the test protocol to determine if a Lombard response would be elicited by the circumstances of this particular study. Figure 3 depicts the change in vocal intensity (in decibels) as a function of speech tasks. The resultant relationship between responses in background noise and responses in quiet is demonstrated for each of the five control subjects. Visual inspection of the results graphed in Figure 3 reveals that

Figure 3. Change in vocal intensity (in dB) as a function of speech task. Five normal hearing talkers demonstrated a change in vocal intensity levels while talking in two noise conditions as compared to talking in quiet during four speech tasks: (C) answer closed questions, (R) read a paragraph, (T) tell a story, and (O) answer open questions.

each control subject demonstrated a systematic increase in vocal intensity level for both the 70 dB SPL and 90 dB SPL conditions when compared to their own responses in the quiet condition. For these subjects, the range of intensity increases across the various speech tasks was 0 to 7 dB for the 70 dB SPL noise condition and the range of increase was 5 to 14 dB for the 90 dB SPL condition.

The first research question was: Will a systematic, measureable change occur in the vocal intensity of a deaf person implanted with a cochlear prosthesis when the subject is exposed to background noise that is manipulated systematically? Figure 4 compares responses of five experimental subjects in two test conditions: cochlear implant off and cochlear implant on. Change in vocal intensity (in decibels) is depicted as a function of speech tasks. The resultant relationship between responses in two conditions of background noise as compared to baseline (quiet background) is illustrated. When their cochlear implants were turned off, the experimental subjects did not demonstrate a systematic increase in vocal intensity with increase in noise. Subjects 3, 4, and 5 showed little change in comparison to their own baseline (speech in quiet condition) in the 70 dB SPL condition. In contrast, Subjects 1 and 2 showed random fluctuation about their baseline for this same condition. In the 90 dB SPL, implant-off condition, Subjects 2 and 3 demonstrated an increase of 4 to

Figure 4. Change in vocal intensity (in dB) is depicted as a function of four speech tasks: (C) answer closed questions, (R) read a paragraph, (T) tell a story, and (O) answer open questions. Responses in two noise conditions are compared to responses at baseline (in quiet) for two variables: implant off and implant on.

5 dB in vocal intensity level. Subjects 1 and 4 showed random fluctuation about their baseline for this same condition. Subject 5 had responses buried in noise and demonstrated no change in vocal intensity level.

When their implants were turned on, three of the experimental subjects (identified as 1, 2, and 3) demonstrated a progressive increase in vocal intensity with increasing background noise. With 70 dB SPL of background noise, they demonstrated a change in intensity that ranged from -1 to 5 dB. With 90 dB SPL background noise, intensity increase ranged from 2 to 9 dB across all speech tasks. Subject 4 demonstrated nonsystematic (random) change in vocal intensity while talking in 90 dB SPL of noise. Subject 5 showed no change in vocal intensity with increasing background noise.

The second research question was: For the cochlear implant patient, is the relation between intensity of vocal output and background noise closer to the normal function when the implant is turned on than when the implant is turned off? The "normal function" is depicted by the graphs derived from responses by the normal hearing subjects and is described as a systematic progression of increasing vocal intensity level as the level of background noise increases. In addition, the definition of the "normal function" pattern must allow for variability in subject responses either when compared to themselves or when compared to others.

A visual comparison of Figures 3 and 4 reveals that the first three experimental subjects had patterns of vocal intensity that were closer to the normal function with their implants turned on than with their implants turned off. With implants turned on, the responses of experimental Subjects 4 and 5 did not move closer to the response patterns of the normal hearing subjects.

Discussion

The control subjects in this study showed variability in the amount of their Lombard response compared to one another and across the four different speech tasks. When the control subject responses in noise were compared to their individual baseline (talking in quiet), they all demonstrated a progressive increase in voice intensity with increase in background noise. These observations are similar to conclusions made by Chailkin and Ventry (1963), Dreher and O'Neill (1957) and Gardner (1966). Specifically, subjects with normal hearing demonstrate variability of vocal intensity response and they demonstrate systematic increase in vocal intensity level with increasing background noise. The five controls are not treated as a sample of a population because of their small number. Instead, they served to establish that the conditions of this study would elicit a Lombard effect. In essence, their responses answered the

question: Was the experimental condition designed appropriately to elicit a Lombard response among subjects who had normal hearing for their age? It is concluded that the conditions of the present study produced expected Lombard effects in persons whose hearing responses are within normal limits for their age.

A second question was asked after examining the results from the control subjects. Is the magnitude of the Lombard response obtained by the conditions of this study similar to results obtained by other researchers? The control subjects' responses across all speech tasks were averaged and graphed. Figure 5 shows the change in vocal intensity (in decibels) as a function of the intensity level of the background noise. The resultant curve is the mean response of the five normal hearing subjects. The ratio of change, that is, the increase in voice intensity (in decibels) for each decibel increase in noise, was 0.24. This ratio is small compared to studies that obtained slopes of 0.30 to 0.50 (Garber et al., 1976; Lane & Tranel, 1971; Siegel et al., 1976; Siegel et al., 1982). Gardner (1966) and Lane and Tranel (1971) emphasized the importance of considering all the factors of a loudness modulation study before making comparisons between studies. The small ratio of change obtained in this study as compared to results reported in other studies, may be related to the levels of background noise chosen to elicit the

Figure 5. Change in vocal intensity (in dB) as a function of the level of background noise with mean response of five normal hearing talkers as the resultant curve. When background noise was increased 20 dB, the five normal hearing talkers demonstrated an average increase in vocal intensity of 0.24 dB for each dB increase in noise.

Lombard response. Garber et al. (1976) concluded that as the intensity of the masking noise is increased it becomes more effective in generating a Lombard effect. A larger ratio of change may have been elicited if the attenuator was set at 80 dB SPL and 100 dB SPL.

A background noise with greater potential for interfering with speech intelligibility might have been chosen for this study. Some studies that elicited enhanced Lombard effects (slope greater than 0.30) used white noise as the background noise. Garber et al. (1976) found white noise

in the 350 to 700-Hz and 1800 to 2500-Hz bands interfered most with speech intelligibility. However, other researchers have found that the babble of many voices is effective in eliciting an enhanced Lombard response (Kalikow & Stevens, 1977; Webster & Klump, 1962). Thus, the choice was not clear between using white noise or the babble of voices for effective masking. In order to predict how a person with a cochlear implant might perform in every day situations, it was decided to simulate conditions occurring naturally for this study. Achieving an enhanced Lombard response may have been sacrificed to achieve "naturalness" of the test conditions.

The conditions of the experiment bear further discussion. Many researchers have noted a relationship between the communication task and its effectiveness in eliciting a Lombard response (Dreher & O'Neill, 1957; Lane & Tranel, 1971; Lane et al., 1970; Webster & Klump, 1962). The present study used a variety of speech tasks. The progression of tasks was designed to require increasing attention by the subjects to the content of their output rather than attending to the production of their speech. Surprisingly, the control subjects, in general, demonstrated the greatest change in vocal intensity during the "closed questions" task under both noise conditions. No one speech task consistently elicited a greater Lombard response than others.

For the experimental subjects, no trend was noted

between the type of implant and the experimental results. In the experimental group demonstrating "no change," each subject was implanted with a different prosthesis. In the cochlear implant group that did demonstrate change, one wore a 3-M Corporation prosthesis and two wore Nucleus prostheses.

The experimental subjects' individual response patterns deserve examination. The variation in intensity responses within individuals and between individuals across the various speech tasks is notable. Experimental Subject 5, who wore a 3-M implant, is an exception. He maintained a consistent response no matter what the task or condition. The results from his performance in this study are consistent with his performance as demonstrated in the clinical setting, that is, consistent, paced, nonvarying vocal intensity. With the exception of Subject 5, experimental subjects tended to be more inconsistent in their responses across the various speech tasks for both the implant-off and the implant-on conditions than were the controls. This may be a demonstration of the fluctuating vocal intensity control problems experienced by many persons who are deaf. Subjects 1 and 2, (wearing Nucleus implants) and Subject 3 (wearing a 3-M implant) showed less random fluctuation with their implants on. This observation leads to the conclusion that they were receiving information helpful in monitoring their own voice when their implants were turned on. Because experimental Subject 5 did not show variation across the

did not demonstrate increase in voice intensity with increasing background noise, it is assumed he is not receiving adequate auditory information, or he has not learned to use the information he receives. It may be conjectured that he maintains his consistent vocal intensity level by relying heavily upon kinesthetic feedback to perceive the amount of vocal effort expended while talking. Or, according to current theory, he may rely upon an internal imaging process to maintain his steady, nonvarying vocal intensity level.

Subject 4 (who wore a Nucleus implant) demonstrated random fluctuation of vocal intensity level in both the implant-off and the implant-on conditions. This may indicate she was not receiving adequate information or that she was not using the information she received. Her fluctuating, random responses noted in this study are consistent with her responses for other dimensions of cochlear implant use as observed in the clinic setting.

Experimental Subject 3 appears to demonstrate a Lombard response in the implant-off, 90 dB SPL noise condition. The response pattern appears too consistent to be labeled as random variation. This apparent Lombard response may be attributed to extreme sensitivity to vibration cues. This subject has demonstrated an acute awareness of environmental cues in the clinic setting. In addition, she has a small amount of residual hearing in the ear contralateral to the

implant and may have been responding to acoustic cues in the unimplanted ear. Similarly, Subject 2 demonstrated a small Lombard response in the implant-off, 90 dB SPL noise condition. He, too, has minimal hearing in the unimplanted ear and may have been responding to minimal auditory cues. In any event, his responses in the implant-on condition (with background noise of either 70 dB SPL or 90 dB SPL) were moved dramatically toward the normal pattern of response both in degree of change and in pattern of change.

Reiterating the conclusions reached earlier, three experimental subjects demonstrated systematic increases in voice intensity with increases in background noise. Although the increases were less than those demonstrated by the control group, they were in the low end of the range of change the controls made. It is concluded that these three subjects regulate their vocal intensity closer to the normal function with their implants turned on. Two of the cochlear implant subjects did not demonstrate systematic change in vocal intensity level with their implants on and did not perform as would be expected for persons receiving adequate auditory information. Interestingly, in the clinic setting, the five experimental subjects demonstrated similar patterns of performance for other dimensions of auditory discrimination while wearing their cochlear implants. Subjects 1, 2, and 3 demonstrated voice intensity increase with increasing background noise that was closer to the

normal function with implants turned on than with implants turned off. In the clinic setting, it was noted also that they demonstrated responses of an exceptional quality to other aspects of cochlear implant use. They showed unusual ability to integrate auditory cues into speechreading, they demonstrated an ability to listen critically to minimal cues, and they incorporated these cues in a synthetic (holistic) manner into their comprehension pattern. Two of them developed the ability to identify some speech without visual cues. They seem to have a unique attribute, that is, the "synthetic generalist" cognitive style of listening. Subjects 4 and 5 did demonstrate improved sound awareness skills and improved speech reading skills with implant on, but their communication skills were inefficient and often lacked effectiveness.

The literature reports that variability in performance in auditory discrimination tasks is typical for cochlear implant subjects. Implant design does not appear to be a major factor influencing performance, for there are "star" performers using each type of implant, just as there are those who receive minimal help from their implants. This variability in performance leads naturally to queries regarding cause. Many researchers indicate that the prime factor for successful use of an implant is the number and placement of excitable nerve fibers remaining (Millar et al., 1984; Miller & Pfingst, 1984). State-of-the-art procedures

have not reached a point where the number of fibers remaining can be determined readily. The other important factors that remain for the clinician to address are motivation, cognitive style, and the ability to listen critically. Whether these factors can be developed, especially in the older client, or whether they are already present and can be enhanced by intervention strategies has not been determined objectively.

In conclusion, it has been noted subjectively in the literature that some deaf persons demonstrate improved vocal loudness regulation as a result of implantation with a cochlear prosthesis. The results of this study quantitatively support this observation. This is not true for all persons receiving a cochlear implant. Precise predictive tests to determine successful use of a cochlear implant are not available currently.

CHAPTER V

SUMMARY AND IMPLICATIONS

Summary

The literature presents a complex model of speech regulation that employs "central imaging" of the motor act of speech preceding production. In addition, this model provides options for regulating speech by sensory feedback. The regulation of intensity relies on feedback more than does the regulation of the timing aspect of speech. Persons who are adventitiously deaf have varying degrees of success in modulating their vocal intensity. They may rely upon central feedback or, at times, may regulate intensity by using tactile, kinesthetic, or social feedback (Lane and Tranel, 1971). Deaf persons experience difficulty in modulating their vocal intensity appropriately in the presence of background noise. Cochlear implants provide hope for improving the communication skills of persons who sustain profound hearing loss. A cochlear implant is an auditory prosthesis designed to stimulate electrically the surviving population of nerve fibers in the cochlea of a deaf person.

In this study, five deaf individuals with cochlear implants were presented with noise that was manipulated

systematically, to test the hypothesis that deaf persons using cochlear prostheses will demonstrate intensity regulation of their vocal output that is more appropriate when their implants are turned on than when turned off. The intensity of their vocal output was measured to determine if they demonstrated a Lombard response, that is, a systematic increase in vocal intensity with increasing intensity of background noise. Results from the study were mixed. With implants on, three subjects made systematic increases in vocal intensity with increasing background noise, while two subjects did not make such increases. In addition, the relation between intensity of vocal output and background noise was closer to the normal function for the three subjects who demonstrated a Lombard response. The "normal function" was defined by measuring the vocal intensity responses of five normal hearing control subjects who performed the same tasks as the experimental subjects.

The results of this study appear consistent with the growing body of information on the effects of cochlear implants gathered from numerous research centers that indicates there is wide variation in performance that cannot be attributed entirely to implant design (Millar et al., 1984; Miller & Pfingst, 1984). Two important factors that appear to influence performance are the number and placement of remaining nerve fibers, and the cognitive style employed by the individual.

Clinical Implications

These are the formative years for developing rehabilitation programs for persons receiving cochlear implants. The more clinicians understand the operation of normal speech-regulating systems, the better they will be able to intervene when regulating systems go awry as in the case of disruption of sensory feedback. Those patients that continue to experience problems with loudness regulation following implantation with a cochlear prosthesis may require intervention to develop strategies for more appropriate speech output. They may need to learn to use voluntary regulation of intensity. It seems of primary importance to deal forthrightly with any self-initiated client behavior that leads to embarrassment, especially a behavior that would increase the possibility of withdrawing from communication opportunities. The deaf are frustrated and feel out of control when they must rely on external sources of control--family, friends, clinicians--for cues for loudness modulation. Confidence and feelings of being in control (internal locus of control) may grow with the knowledge that hearing persons are not dependent upon auditory feedback alone, but base judgments for loudness modulation on cues other than auditory. A person using a cochlear implant can be encouraged to make bold use of minimal auditory cues and

to build awareness of other cues for more effective communication. Clinically, the following approaches appear feasible; counseling and education, training in critical listening for minimal cues, and using voluntary control based on cues other than auditory. The efficacy of these approaches has not been proven. Those cochlear implant clients whose behaviors are closer to the normal response with implant on as compared to implant off may also benefit from intervention to "fine tune" their responses. The limits of their use of cochlear implants have not been established.

Research Implications

At this point in cochlear implant research, there is a need to delineate candidacy issues. There is widespread misunderstanding regarding the amount of information a cochlear implant can provide. The responses of some "star" subjects can mislead the public into assuming the deaf will be able to hear normally. Indeed, unrealistic hopes for dramatic return of hearing can hinder the rehabilitation progress. There is a need for a predictive measure to determine pre-operatively what the projected hearing outcome will be and to aid in the selection of type of implant most appropriate for the client.

One of the factors correlated with successful use of a cochlear implant is assumed to be the number and placement of

the remaining nerve fibers in the cochlea. At present, the presence of nerve fibers can be estimated roughly from a battery of psychophysical tests, including electrical stimulation of the cochlea, administered prior to implantation. There is a need to enlarge the scope of the pre-implantation tests that will be predictive of successful implant use. The results of this study suggested that those individuals who achieved significant benefit from a cochlear implant also demonstrated a Lombard response when talking in noise. These findings imply that testing for the presence of a Lombard response during pre-implant electrical stimulation may be predictive of successful implant use.

This study raised many questions regarding the efficacy of rehabilitation programs for persons with cochlear implants. Is it possible to train loudness modulation, and if so, what form would the training model take? Would an effective clinical model include 1) build awareness of minimal cues to regulate loudness, 2) develop and rehearse the skill in a supportive environment, 3) apply the skill in a hierarchy of stressful situations? Further trials with such a model are needed. Questions that arise include: What are the significant factors for building improved loudness modulation? Will persons with a cochlear implant learn to use electrical stimulation merely by experiencing it on a daily basis, or do they benefit from intervention? What are reasonable expectations for the time it takes to adjust to

electrical stimulation and to demonstrate changes in speech output? For those cochlear implant subjects who do not demonstrate appropriate loudness modulation, does the problem lie in not receiving enough information via their implant, or is the problem based on their not making good use of the minimal cues they do receive. As other researchers have pointed out, cognitive style appears to be a decisive factor in effective use of a cochlear implant. Is it possible to train a more synthetic approach to listening? What form would a clinical program take to accomplish this? Very little information is available in the literature on the effects of treatment on cochlear implant use.

The years of experimentation with electrical stimulation are coming to fruition bringing hope to many who are deaf. Opportunities abound for continued research into all aspects of cochlear implants especially in the areas of understanding the mechanism of the ear, improving technology for replacing the function of the hair cells, and developing rehabilitation programs designed to aid the implantee to live with a new way of hearing.

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APPENDIX A

COCHLEAR IMPLANT REHABILITATION PROGRAM

Department of Audiology

and

Rehabilitation of Oregon Outpatient Program

Speech and Language Pathology Services

Good Samaritan Hospital and Medical Center

Portland, Oregon

The audiologist and the speech-language pathologist on the cochlear-implant team direct the training phase of rehabilitation for cochlear implant patients at Good Samaritan Hospital and Medical Center. The main goal of the program is to aid clients with cochlear implants to augment their communication skills. In essence, the clients build tolerance for listening to electrical stimulation and learn to use minimal changes in signal advantageously for processing sound. During the first few months of experience with electrical stimulation, the audiologist works frequently with the client to adjust the internal settings of the processor. Over time, the client tolerates more sound and develops a critical awareness of the small differences in sound that are received. Adjusting the processor can be a trial and error process. It relies upon client report for

descriptions of the sound sensations received. The audiologist and client must determine a mutually-understood vocabulary to assure accurate, consistent reporting.

The audiologist's role is to:

- 1) monitor progress through systematic objective testing
- 2) set and adjust the stimulator
- 3) fit and adjust the external holding apparatus
- 4) instruct the client in use of the equipment
- 5) train the client in critical listening for environmental sounds
- 6) provide counseling for client, spouse, and family to increase their understanding and acceptance of listening to electrical stimulation and to build realistic expectations for outcome
- 7) determine optimal settings for the processor

The speech-language pathologist works with the client to establish communication competence and to develop skills in managing independently the problems that are related to hearing loss. This goal is accomplished by developing specific skills in the following.

- 1) Critical listening is developed by building awareness of cues, listening for minimal differences, learning to count beats of words, and learning to rank sounds.
- 2) Speechreading is taught in conjunction with using a cochlear implant. The client learns to integrate auditory cues to aid speechreading. Speechreading skills are enhanced

by identifying and applying strategies that prevent and repair communication breakdowns. In addition, the principle of taking responsibility for one's own communication is emphasized.

3) Coping with a communication handicap is an important aspect of the program. In a group setting, clients identify barriers to communication, develop options to overcome the barriers and practice their new skills in a supportive environment.

4) Speech intelligibility and acceptability, is monitored and intervention is provided when necessary.

The program includes group and individual intervention sessions with the cochlear implant patients. Spouses are included in the group and individual sessions. Typically, an individualized telephone code system is developed according to each client's needs.

APPENDIX B

INFORMED CONSENT

I, _____, hereby agree to serve as a subject in the research project conducted by Carol Ross.

I understand the study involves answering questions, reading a paragraph and retelling a story told to me by the investigator. My responses will be tape recorded. There will be background noise present during the study. It has been explained to me that the purpose of the study is to learn some effects of a cochlear implant upon speech.

I may not receive any direct benefit from participating in this study, but my participation may help to increase knowledge which may benefit others in the future.

Carol Ross has offered to answer questions I may have about the study and explain what is expected of me.

I understand I am free to withdraw from participation in this study at any time without jeopardizing my relationship with Portland State University.

I have read and understand the foregoing information.

Date _____ Signature _____

If you experience problems that are the result of your participation in this study, please contact Richard Streeter, Office of Graduate Studies and Research, 105 Neuberger Hall, Portland State University, 229-3423.

INFORMED CONSENT

I, _____, hereby agree to serve as a subject in the research project conducted by Carol Ross at Good Samaritan Hospital and Medical Center.

It has been explained to me that the purpose of this study is to learn some of the effects of a cochlear implant upon speech. My part in the study will take up to two hours of participation. I understand I will answer questions, read a paragraph, and retell a story told to me previously by the investigators. My responses will be tape recorded. There will be background noise present for short periods of time during the study.

I understand that confidentiality of records identifying me as a subject will be maintained.

Carol Ross, telephone number 229-7715, has offered to answer any questions I may have about this study and to explain what is expected of me.

I understand I am free to refuse to participate or to withdraw from participation in this study at any time and it will in no way affect my relationship with, or treatment at, Good Samaritan Hospital and Medical Center. It was explained to me it is not the policy of Good Samaritan Hospital and Medical Center, or any other agency funding the research project in which I am participating, to compensate or provide medical treatment for human subjects in the event the

research results in physical injury. I further understand that should I suffer any injury from the research project, compensation will be available only if I establish that the injury occurred through the fault of Good Samaritan Hospital, its officers or employees or physicians. (Further information regarding this policy may be obtained from the Office of Research Administration at 229-7218.)

I have read and understand the foregoing.

Date _____ Signature _____

APPENDIX C

SPEECH MATERIALS

1. Please answer in complete sentences:

What is your name?

What year is this?

In what city and state is this hospital located?

What is the name of this hospital?

What river runs through Portland?

What is Portland's nickname?

2. Read this paragraph outloud, please.

You wish to know all about my grandfather. Well, he is nearly 93 years old, yet he still thinks as swiftly as ever. He dresses himself in an old black frock coat, usually several buttons missing. A long beard clings to his chin, giving those who observe him a pronounced feeling of the utmost respect. When he speaks, his voice is just a bit cracked and quivers a bit. Twice each day grandfather plays skillfully and with zest upon a small organ. Except in the winter when the snow or ice prevents, he slowly takes a short

walk in the open air each day. We have often urged him to walk more and smoke less, but he always answers, "banana oil!" Grandfather likes to be modern in his language.

(Darley, 1975)

3. Please retell the joke you read earlier.

One day Adam said to Eve, "I'm going out hunting and won't be home for dinner." But Adam came home much later than he had planned. Eve looked at him through narrowed eyes and said, "Where have you been all day?"

Adam replied, "Hunting, naturally."

Eve said suspiciously, "You're keeping something from me--you have met someone!"

"My dear Eve," answered Adam, "You know we are the only people on earth."

Eve didn't say anything, but later that night she counted his ribs.

4. Answer these questions:

What is your opinion of Portland's weather?

What do you like to do when it rains?

Do you think Portland's weather provides an advantage or is a drawback to living here?

APPENDIX D

WAVEFORM READING

Photographs were taken of speech waveforms stored on the oscilloscope screen. Waveforms of words spoken in isolation by one investigator served as references. The energy patterns of the waveforms were matched with the phonetic features of the words.

HOSPITAL

NAME

RIVER

NINETEEN

ROSES

SEVERAL

GRANDFATHER

Isolated word
is shown.

THINKS AS SWI-

Connected speech is
shown. Cursors
measure the
amplitude of the
vowel in "thinks."

Voltage difference measurements were obtained by moving the volts-cursor function reference lines to measure the peak-to-peak vertical deflection of the concentration of energy for a stressed syllable. Individual spikes of energy extending beyond the main body of energy for a syllable were omitted if they represented less than one-fourth of the syllable energy. This was an arbitrary criterion designed to promote consistency in reading from day to day and to determine a value that represented best the energy of the syllable.

The word "grandfather" as spoken by a normal hearing subject is shown in Picture 1: a quiet background, in Picture 2: in 70 dB SPL noise, and in Picture 3: in 90 dB SPL noise. The waveforms for the 70 dB and 90 dB SPL background noise may be seen between the syllables in Pictures 2 and 3. There is a progressive increase in vertical deflection of the background noise with increasing intensity of the noise and a corresponding increase in vertical deflection of the waveform "grandfather." In each photograph, the cursors are pictured measuring the first syllable of the word grandfather.

Picture 1. "Grandfather"
spoken in a quiet
background.

Picture 2. "Grandfather"
spoken in 70 dB SPL
background noise.

Picture 3. "Grandfather"
spoken in 90 dB SPL
background noise.

APPENDIX E

DESCRIPTIVE STATISTICS OF NORMAL HEARING SUBJECT

SUB- JECT	BACK- GROUND LEVEL	-----MILLIVOLTS-----			DB RATIO
		MEAN	S.D.	RATIO	
A	QUIET	1.08	0.41	-	-
	70-DB	1.70	0.53	1.57	3.93
	90-DB	3.46	0.58	3.22	10.15
B	QUIET	1.27	0.45	-	-
	70-DB	2.06	0.67	1.63	4.24
	90-DB	3.73	0.52	2.95	9.39
C	QUIET	1.40	0.47	-	-
	70-DB	1.57	0.38	1.13	1.05
	90-DB	2.81	0.48	2.02	6.10
D	QUIET	1.23	0.29	-	-
	70-DB	1.45	0.39	1.18	1.40
	90-DB	2.25	0.38	1.83	5.26
E	QUIET	1.60	0.71	-	-
	70-DB	2.39	0.88	1.50	3.49
	90-DB	3.79	0.69	2.37	7.51

DESCRIPTIVE STATISTICS
OF EXPERIMENTAL SUBJECTS

		IMPLANT ON.....				IMPLANT OFF.....			
SUB- JECT	BK GND LEVEL	---MILLIVOLTS---			DB RATIO	---MILLIVOLTS---			DB RATIO
		MEAN	S.D.	RATIO		MEAN	S.D.	RATIO	
1	QUIET	1.55	0.45	-	-	1.68	0.43	-	-
	70-DB	1.91	0.59	1.23	1.83	1.40	0.45	0.83	-1.60
	90-DB	2.71	0.57	1.75	4.87	1.95	0.40	1.16	1.27
2	QUIET	0.92	0.22	-	-	1.07	0.31	-	-
	70-DB	1.32	0.41	1.45	3.22	0.91	0.25	0.75	-2.47
	90-DB	1.67	0.31	1.80	5.12	1.45	0.22	1.36	2.64
3	QUIET	1.17	0.41	-	-	1.38	0.39	-	-
	70-DB	1.36	0.44	1.16	1.27	1.40	0.36	1.14	1.10
	90-DB	1.97	0.46	1.68	4.50	2.19	0.26	1.60	4.04
4	QUIET	0.98	0.36	-	-	0.90	0.25	-	-
	70-DB	1.13	0.41	1.15	1.22	0.91	0.28	1.39	2.83
	90-DB	0.86	0.17	1.28	2.12	-	-	-	-
5	QUIET	0.82	0.36	-	-	0.80	0.38	-	-
	70-DB	0.86	0.36	1.05	0.43	0.84	0.39	1.05	0.40
	90-DB	-	-	-	-	-	-	-	-