Cognitive Factors and Cochlear Implants: An Overview of the Role of Perception, Attention, Learning and Memory in Speech Perception[1]

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Abstract. Over the last few years, there has been increased interest in studying the cognitive factors that affect speech perception performance of cochlear implant patients. In this paper, I provide a brief theoretical overview of the information processing approach to cognition and discuss the role of perceptual learning, attention and memory in speech perception and spoken language processing. Directions for future research on information processing issues are discussed with the goal of predicting success with a cochlear implant from a set of cognitive measures of performance.

Introduction

We are now beginning to see several important changes in the direction and nature of research on cochlear implants, particularly research on very young prelinguistically deaf children who have received cochlear implants. As cochlear implants and their speech processing strategies improve, more and more deaf children are able to derive greater benefit from their implants. Many of these children display substantial gains in speech perception, word recognition and language development (Fryauf-Bertschy, Tyler, Kelsay, & Gantz, 1992; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Miyamoto, Kirk, Robbins, Todd, Riley, & Pisoni, 1997; Miyamoto, Svirsky, & Robbins, 1997; Waltzman et al., 1997). And, many prelinguistically deafened children with CI's somehow learn how to produce intelligible speech within one year of implantation and appear to be well on their way to acquiring a grammar of spoken language via their CI (Miyamoto, Svirsky et al., 1997; Robbins, Svirsky, & Kirk, in press). How do they accomplish this difficult task?

As performance levels on standardized audiological tests continue to improve, a number of researchers have turned their efforts to gaining a better understanding of several more basic questions that surround how cochlear implants function to facilitate cognitive and linguistic development in deaf children (Kirk, Pisoni, & Miyamoto, in press; Kirk, Pisoni, & Osberger, 1995; Miyamoto, Svirsky et al., 1997; Robbins, Svirsky, & Kirk, in press). These new questions deal with a variety of issues involving the perception of speech and spoken language understanding. More generally, the interest is starting to shift to questions of how deaf children encode and process information using a cochlear implant. Many of these questions concern fundamental issues of human information processing and involve topics such as perceptual learning, memory, attention and language processing, research areas that have traditionally been in the mainstream of Cognitive Psychology (Ashcraft, 1989; Atkinson & Shiffrin, 1968; Crowder, 1976; Haber, 1969) and Cognitive Science (Gardner, 1985).

Much of the past research on CI's has been concerned with questions of assessment and device efficacy using outcome measures that were based on traditional audiological criteria. These measures included a variety of hearing tests, speech discrimination, word recognition and comprehension tests, as well as some standardized vocabulary and language assessments. The major focus of this research over the last 10-15 years has been concerned with the study of demographic variables as predictors of these outcome measures. The available evidence demonstrates that age at onset of deafness, length of deprivation and age at implantation play substantial roles in predicting many of the standard outcome measures

(Fryauf-Bertschy et al., 1997; Kirk et al., in press; Osberger, Todd, Berry, Robbins, & Miyamoto, 1991; Staller, Pelter, Brimacombe, Mecklenberg, & Arndt, 1991; Waltzman et al., 1994, 1997). What happens if you eliminate the demographic variables? What is left over to study? We suggest there are a number of "process" variables or factors that are related to learning, memory, attention and language processing that have been ignored over the years. We feel that these particular areas of research are critical to gaining new insights into how children acquire language through a cochlear implant and explaining the enormous individual differences among prelingually deaf children with cochlear implants.

The child's early sensory experience has also been shown to have a significant role in predicting outcome measures. It should not come as a surprise to anyone that deaf children from "oral-only" programs do consistently better on auditory-based tests of speech perception and language performance than deaf children from total communication (or TC, i.e., manually-coded language plus speech) programs (Kirk, 1996; Miyamoto, Kirk et al., 1997; Robbins, Kirk, Osberger, & Ertmer, 1995). The study of demographics and the focus on traditional audiological outcome measures in these children are only a small part of the story of what is actually going on. To gain a better understanding of what these children are learning via their implant, it is necessary to approach this problem from an entirely different theoretical perspective and to look more closely at the content and flow of information and how it changes over time and study the underlying processes.

Little, if any, of the previous research on cochlear implants has been concerned with studying what the children are learning via their implant, how they are going about the process of acquiring a grammar from the ambient language or how they are able to develop both receptive and expressive language abilities. Moreover, until recently there have been very few attempts to study the language development of children with CI's and compare their linguistic knowledge and performance with normal hearing children or with other hearing-impaired children (Miyamoto, Svirsky et al., 1997; Robbins & Kirk, 1996). These are important questions that go well beyond surface issues of assessment, device efficacy, or simply predicting outcome measures; they are fundamental questions that deal with the "effectiveness" of cochlear implants outside the special conditions of the clinic or the research laboratory. The major emphasis on assessment-based clinical research and the prediction of outcome measures is changing now, and there are several papers at this meeting that report new findings on some of these important new questions (Kirk et al., in press; Pisoni, Svirsky, Kirk, & Miyamoto, this volume; Robbins et al., in press; Zwolan et al., 1997).

In order to explore some of these new research questions and to move beyond the study of demographics and the issues surrounding assessment and prediction of outcome measures, it is necessary to look to other allied disciplines such as Cognitive Psychology (Haber, 1969; Neiser, 1967; Reitman, 1965) and Cognitive Science (Gardner, 1985). New experimental methods and techniques must be used to study the emergence of these fundamental underlying cognitive and neural processes and how these processes change over time after implantation. Fortunately, many useful experimental procedures have already been developed by cognitive psychologists to study perception, attention, learning and memory within the framework of human information processing (Haber, 1969; Lachman, Lachman, & Butterfield, 1979; Neisser, 1967). This approach has also provided a variety of conceptual tools for thinking about the fundamental structures and processes involved in cognitive activity and the underlying psychological phenomena (Lindsay & Norman, 1977; Reitman, 1965).

"Information processing" is a label for a general approach to the study of complex psychological processes such as perception, cognition and thought (Haber, 1969; Neisser, 1967). Information processing theories are concerned with an analysis of "central processes" of large complex systems (such as human cognition) used in visual object recognition, perceptual learning and memory, speech perception, and various aspects of language processing such as comprehension or speech production. A common goal of this approach is to examine the representations, elementary psychological processes and cognitive structures used in these cognitive activities and to trace out the time course of these processing operations (Haber, 1969; Lachman et al., 1979; Sternberg, 1966, 1969).

In the sections below, I first give a very brief overview of the major theoretical assumptions of this approach to cognition and to areas of research such as perception, attention, learning and memory. Then, I will examine several new directions for future research on cochlear implants that are motivated by the major assumptions of the information processing framework. I believe it may now be possible to understand and explain the large individual differences observed in children and adults with cochlear implants by studying the psychological and cognitive factors and the component subsystems used in perception, attention, learning and memory. This is one of many problems that can now be approached with some confidence within this theoretical framework.

Overview of the Information Processing Approach

Assumption I: Perception is Not Immediate

One of the fundamental principles of information processing theory is that sensation, perception, memory, thought and other complex activities like language and problem solving should be viewed as representing a continuum of cognitive processing (Haber, 1969; Neisser, 1967). These activities are assumed to be mutually interdependent and cannot be divided up into separate subsystems. Furthermore, an analysis of one subsystem, such as perception, cannot take place without an appreciation and awareness of the contribution of the other major subsystems, such as memory, attention or learning (Haber, 1969; Neisser, 1967; Reitman, 1965).

The information processing approach to cognition also assumes that processing activity goes through several successive stages of analysis. One goal of information processing theory is to specify the component operations that occur between the presentation of a stimulus and the response of the observer. The processing stages between input and output are typically represented by a flow chart with structures and processes organized in a block diagram. The flow of information is marked by arrows connecting these structures (Haber, 1969).

These hypothesized processing stages also take time. It is assumed that processing times reflect distinct operations that occur at each stage (Baddeley, 1986). By looking at the correlations between the contents of the stimulus and the contents of the observer's response at various times after stimulation, some insights can be gained about the flow of information within the system and the nature of the operations being carried out at each stage of processing (Haber, 1969; Neisser, 1967; Reitman, 1965).

Finally, the information processing approach assumes that psychological processes such as sensation, perception, attention, learning and memory are organized hierarchically. More complex cognitive processes which occur later in the flow of information are critically dependent on earlier more elementary psychological processes (Atkinson & Shiffrin, 1968; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

Assumption II: Capacity Limitations on Processing Information

A second principle of information processing theory is that the human observer has finite information processing capabilities and displays severe channel capacity limitations in a variety of tasks (Broadbent, 1958; Miller, 1956; Waugh & Norman, 1965). Years ago it was believed that the nervous system was not large enough to maintain all aspects of stimulation permanently and that raw sensory information needed to be transformed, reduced and recoded into a more efficient symbolic form for storage in memory (Neisser, 1967). A central problem in information processing theory is identifying the "locus" of where recoding takes place in the processing system and describing the nature of these processing operations (Kahnman, 1973; Shiffrin, 1988). Thus, research in cognitive psychology on topics such as selective attention (Cherry, 1953; Lindsay & Norman, 1977; Shiffrin, 1988) and immediate memory span (Baddeley & Hitch, 1974; Miller, 1956; Waugh & Norman, 1965) demonstrate that not all aspects of the stimulus environment are encoded or processed by the nervous system or stored in permanent memory for later retrieval (Cowan, 1988; Navon & Gopher, 1979). Understanding the process of "information reduction" and "recoding" by the nervous system has been a long-standing problem that cuts across several domains including perception, attention, learning and categorization (Baddeley, 1990; Posner, 1969).

Assumption III: Commonality of Perception and Memory

A third principle of information processing theory is that all aspects of cognitive activity—ranging from sensation and perception to learning and thought—involve some kind of storage or memory system that preserves selected aspects of the initial sensory stimulation (Atkinson & Shiffrin, 1968; Lindsay & Norman, 1977; Posner, 1969; Waugh & Norman, 1965). Thus, the nature of the neural representations of the stimulus in memory and the organization of this knowledge is a fundamental problem in all information processing analyses. The operations involved in encoding, rehearsal, storage and retrieval of information occur at all stages of processing (Atkinson & Shiffrin, 1968). This theoretical approach also assumes that it is not possible to separate the processes that support perception from those that support memory. The two processes are mutually dependent. Memory is therefore one of the central problems to be studied in understanding psychological activities within information processing theory. Encoding, storage, retrieval and rehearsal of the stimulus input all take place within this common subsystem (Atkinson & Shiffrin, 1968; Baddeley, 1986, 1990; Baddeley & Hitch, 1974; Craik & Lockhart, 1972; Posner & Mitchell, 1967).

Goals of Information Processing Approach

The information processing approach is concerned primarily with the "central" cognitive processes used in large systems to carry out complex activities such as perception, learning, memory, language processing and problem solving. The goals of this approach follow from the three principles described earlier. First, information processing theory focuses research on describing the sequence of operations, or "stages of processing," used in a particular task. Second, this approach is concerned with identifying the "locus" of capacity limitations in processing information. Third, this approach attempts to trace the "time-course" of perceptual processing from the stimulus input that impinges on the nervous system to the observer's overt response. Fourth, researchers working within the information processing approach attempt to construct process models and computer simulations of various subsystems in order to formalize and make precise quantitative statements about their performance (Hunt, 1978; Lindsay & Norman, 1977; McClelland & Elman, 1986; McClelland & Rumelhart, 1986; Rumelhart & McClelland, 1986). These models provide detailed explanations of phenomena and make explicit predictions. Finally, over the last few years, researchers working within this general framework have tried to establish the neural plausibility of their models (e.g., McClellan & Rumelhart, 1986; Rumelhart & McClelland, 1986). In the past, most cognitive psychologists expressed little, if any, interest in brain modeling. Their concern was with the flow of abstract symbolic information within the information processing system and with the correlations between stimulus and response at various points in time after stimulation terminated. This situation is changing now as new concepts and techniques from neural networks and connectionist models become available to permit the construction of neurally-inspired models that have some relationship to what is currently known about the nervous system and brain function.

Methodology of Converging Operations

An important methodological principle of the information processing approach is the emphasis on "converging operations" (Garner, Hake, & Eriksen, 1956; Haber, 1969). The idea here is to obtain data on the flow and content of information within the processing system using a wide variety of experimental techniques and research designs and to search for commonalties across different tasks. It is also assumed that the processing activities at different stages can be revealed by two general measures of an observer's behavior: the accuracy of performance and the time required to perform a given task (Hunt, 1978; Lachman et al., 1979; Sternberg, 1966, 1969). Both measures have a long history in the field of experimental psychology and both measures have provided a great deal of valuable information about the component elementary psychological operations used to carry out a particular task. Researchers have also been interested in examining the incorrect responses of subjects in a variety of experimental paradigms in order to analyze error patterns. Errors are often quite systematic and provide new insights into the way human perceivers use partial stimulus information to structure their responses. All of these measures provide information about the underlying cognitive processes being studied.

Some New Research Directions on Cochlear Implants in Children

Language Development vs. Hearing

The bulk of research on cochlear implants has been carried out by audiologists and hearing scientists who have been concerned with the sensory coding of speech by the peripheral nervous system. Only recently have researchers begun to examine the effects of cochlear implants on specific aspects of language development. One very important area of research on language development concerns the child's phonological system which encodes and represents the inventory of sounds the child has acquired and the sound contrasts of the ambient language (Chin, Pisoni, & Svec, 1993).

In order for a child to produce intelligible speech, he must have an organized system for encoding and representing sound patterns in memory, a phonology, and a set of procedures to translate these phonological representations and rules into sensory-motor commands and gestures that can control the vocal tract and articulators in speech production. It is generally assumed that the child has one common phonological system of representation that is used for both speech perception and speech production. Unfortunately, very little is currently known about the phonological systems of prelinguistic deaf children with cochlear implants. Research on this topic has not generated much interest among audiologists, who are concerned primarily with hearing and the peripheral auditory system. Only recently have clinical phonologists begun to seriously study this problem in deaf children with cochlear implants (Chin & Kirk, in press; Chin et al., 1993). These findings indicate that deaf children with cochlear implants display several commonalties with normal-hearing children in terms of their inventory of sounds and the patterning of these sounds in production (Chin et al., 1993).

The same situation is also true for the study of spoken word recognition and lexical access, two subcomponents of the language comprehension system. Little, if any, research has been done on the organization of the child's developing lexicon or the nature of the lexical representations of words that are constructed by deaf children with cochlear implants (Kirk, 1996; Kirk et al., 1995). Some recent evidence suggests that deaf children with cochlear implants perceive and represent spoken words in terms of broad phonetic categories or functional equivalence classes that reflect their inability to reliably discriminate fine phonetic differences in place and voicing (Pisoni, Svirsky, Kirk, & Miyamoto, this volume). Difficulty in perceiving and encoding phonetic distinctions among sound patterns would in all likelihood influence the organization and structural arrangement of words in the lexicon (see Logan, 1992), and would no doubt produce parallel changes in speech and language production as well. These are two topics that are being explored in our research laboratory.

At the present time, very little research has been carried out on morphological and syntactic development in deaf children with cochlear implants. This is a critical area of language development that needs to be investigated in greater depth in order to determine whether children can acquire abstract linguistic knowledge about the grammar of the target language through a processing device that presents their nervous system with a highly degraded and impoverished electrical signal. The key question here is whether deaf children can acquire the full range of morphological contrasts and structural regularities of English when they can represent the sound contrasts of the language only in terms of broad manner classes. What kind of morphological system will these children actually come up with and how is it different from the system normal-hearing children develop? This is obviously an interesting and important research problem because it deals with the interface between phonology and syntax.

Perception and Production

Historically, the fields of speech perception and production have developed independently of each other. In deaf children who have received cochlear implants, it may be necessary to study the development of both processes together in order to gain insights into the underlying linguistic system of the child. Recent findings have demonstrated unusually high correlations between open-set word recognition scores and measures of speech intelligibility (Pisoni et al., this volume). We need to learn more about the child's acquisition and use of phonological information. Specifically, we want to know whether their systems reflect language universals or a coding limitation of the cochlear implant regarding certain phonetic features of the speech signal like place and voicing. Recent findings suggest a common source of variance underlying word recognition and speech intelligibility that involves the phonological representations of words and the mapping of sound patterns onto meanings in memory (Pisoni et al., this volume). Whatever linguistic skills or abilities these children employ in recognizing words in isolation (i.e., without any context or retrieval cues) also appear to be recruited in speech production. The pattern of intercorrelations we have found in our recent analysis of the "Stars" suggests a common underlying representational system for phonological knowledge in memory.

Multimodal Speech Perception

Although many researchers and theorists have traditionally viewed speech perception and spoken language processing as purely acoustic/auditory operations, recent findings on multimodal perception (Massaro, 1998) have provided many reliable demonstrations of the visual/optical correlates for speech perception as represented in the dynamic changes in the talker's face and lips. This topic has many implications for the hearing-impaired because these perceivers often rely heavily on information in the optical display of a talker's face as an aid to speech perception. If speech is viewed within the theoretical framework of event perception as a perceptual system having both acoustic and optical correlates (Auer & Bernstein, 1997; Gaver, 1993), then our view of the task confronting the perceiver must be modified accordingly to fully acknowledge the multimodal properties of speech and the lawful relations between auditory and visual speech cues. Normal-hearing listeners often have difficulty dissociating these two sensory inputs and respond in ways suggesting an integrated perceptual pattern.

These observations about multimodal speech perception are relevant to several recent findings showing interference and inhibition effects of manual communication skills in TC children who are learning oral language via their cochlear implant. In these TC children, knowledge and use of sign language apparently competes with the dominant mode of processing speech via the auditory/phonetic modality. The differences in modality between sign language and speech apparently prevents these TC children from integrating common information across sensory modalities, therefore increasing the processing load on working memory which is assumed to play a major role in language comprehension and word recognition (Baddeley, Gathercole & Papagno, 1998).

Perceptual and Cognitive Development

Many basic questions about perceptual and cognitive development have not yet been studied in deaf children with cochlear implants. At this time, we know very little about the perceptual learning abilities of these children or how auditory and visual attention is shaped and modified by awareness of sound and perception of speech after long periods of sensory deprivation (Lenneberg, 1967). Almost no research has been done on categorization or concept learning in these children. Similarly, we know almost nothing about their working memory systems, a key factor in acquiring new words and producing spoken language using phonological knowledge previously stored in memory (Baddeley et al., 1998). Finally, we currently have no systematic knowledge or information about the metalinguistic abilities of deaf children with cochlear implants. It seems reasonable at this point to wonder if the children who have acquired some rudimentary language skills via their implant also have explicit metalinguistic abilities to reason about and communicate about spoken language as an abstract system. Results from the reading literature suggest that metalinguistic awareness is a strong predictor of early reading success. Is the same relationship true of deaf children with cochlear implants?

Looking at the "Stars"—Studies of the Exceptional Users of Cochlear Implants

The published literature on cochlear implants has consistently reported large individual differences among users. Some prelinguistically deaf children do exceptionally well with their implants, and go on to acquire spoken language and produce intelligible speech. Other children, however, develop only an awareness of sound and never appear to acquire language or produce intelligible speech to the same degree or proficiency as the exceptionally good users. We are now just beginning to examine the performance of the exceptionally good users of cochlear implants, the so-called "Stars," on a variety of behavioral measures including open- and closed-set speech perception tests, word recognition, and vocabulary tests, as well as expressive and receptive language development (Pisoni et al., this volume). Our analyses of the intercorrelations of these measures suggest that the "Stars" have developed a representational system, that is, a phonology and a lexicon for mapping sounds onto meanings. Their exceptionally good abilities in recognizing words spoken in isolation are not restricted to only open-set word recognition tasks. The "Stars" display very good performance on several other tasks, all of which apparently require access to and use of words stored in the lexicon. The pattern of intercorrelations with other behavioral measures was extremely strong for the Reynell expressive and receptive language scales (Pisoni et al., this volume). These recent findings show that the children who do well on open-set speech perception and word recognition skills also do well on other language measures. Finally, one of the most important discoveries from our analysis were the high intercorrelations of the open-set word recognition tests with measures of speech intelligibility. Whatever skills, abilities or processes children use to recognize isolated words in an open-set format, these same processes also appear to be recruited in speech production when the child has to access sensory-motor patterns in order to repeat back spoken words.

Assessment-Based vs. Theory-Driven Research

The primary focus of most of the past research on cochlear implants in children has been on device efficacy and predicting outcome measures using standardized audiological tests. Because of these goals, researchers have tended to concentrate on the study of demographic variables as predictors of success with a cochlear implant. Until recently, these were the only independent variables that were included in the research designs used to study the performance of children with cochlear implants. This is not too surprising given the theoretical orientation and research background of most of the investigators who work on cochlear implants. Audiologists are trained in hearing assessment and traditionally they have had very little interest or motivation in underlying theory. In fact, one could argue that the field of audiology is, for the most part, atheoretical in its approach to hearing and speech perception. The situation is now changing in several respects as the research questions focus in on a variety of new issues surrounding what the child is learning via the cochlear implant and how the cochlear implant works in a functional way.

As we noted earlier, these are research questions that deal with psychological processing activities underlying the actual use of the cochlear implant. Fundamental questions about perception, learning, memory, attention and language which lie outside the domain of clinical audiology or hearing science, can all be approached within the framework of information processing theory because of its concern with describing the underlying psychological processes and mechanisms that intervene between stimulus input and response output. Viewed within this broader theoretical context, many of the difficult "central processing" issues surrounding topics such as individual differences, the time-course of language development, and the relations between speech perception and speech production can now be approached using a variety of new concepts and experimental techniques. The emphasis on demographics no longer has to be the primary focus of research on deaf children with cochlear implants. There are many more important new questions to study.

The shift from "assessment-based" research to "hypothesis testing" and theory-driven research represents a natural progression as researchers move from simple description and device "efficacy" questions to explanation, prediction, and "effectiveness" issues. Fundamentally, we want to know what deaf children are learning via their cochlear implant and how they manage to accomplish this task. Answers to these basic questions about underlying psychological process may have broad implications for new approaches to processor design, aural rehabilitation, and decision making with prelinguistically deaf children. The findings that some deaf children with cochlear implants can perceive speech and produce spoken language is very encouraging because it demonstrates device "efficacy." That is, cochlear implants work with some deaf children, and these children appear to acquire spoken language in spite of using a highly degraded and impoverished electrical signal. However, we do not know how this is accomplished in the exceptionally good children like the "Stars" nor do we know why other children have more difficulty in reaching these important goals. If we had some better ideas and specific hypotheses about what psychological processes and mechanisms were responsible for the exceptionally good performance of the "Stars," we might be able develop new intervention techniques to accelerate and improve the perceptual learning and language development of the "average" user of a cochlear implant. It is very unlikely that changes like this would ever come about by continuing to do descriptive assessment-based research with these children using the traditional measurement techniques from hearing science and clinical audiology. What is needed now is an integrated theoretical framework for studying perceptual learning in these children and relating these findings to performance on speech and language tests.

We believe the information processing approach to complex psychological activities has a great deal to offer at this time. We are encouraged already by several new findings on the "Stars" who display exceptionally good performance on a wide variety of behavioral tests of speech perception and language processing. The "Stars" no longer need to be viewed as anomalies, but may instead provide deep insights into the underlying cognitive processes that are responsible for their superior performance across many different tests. This theoretical framework should also provide us with new ways to study and understand the time-course of perceptual and cognitive development and the interrelations between speech perception and production in these children. Hopefully, these new research directions will help us to understand the role of the environment and the effects of early experience on language development during the critical period when the child's nervous system is still amenable to change.

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