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Is There a Critical Period for Cochlear Implantation in Congenitally Deaf Children? Analyses of Hearing and Speech Perception Performance after Implantation

ABSTRACT: *A range of basic and applied studies have demonstrated that during the development of the auditory system, early experimental manipulations or clinical interventions are generally more effective than those made later. We present a short review of these studies. We investigated this age-related plasticity in relation to the timing of cochlear implantation in deaf-from-birth children. Cochlear implantation is a standard intervention for providing hearing in children with severe to profound deafness. An important practical question is whether there is a critical period or cutoff age of implantation after which hearing outcomes are significantly reduced. In this article, we present data from prelingually deaf children (mostly congenitally deaf) implanted at ages ranging from 1 to 15 years. Each child was tested with auditory and speech understanding tests before implantation, and at regular intervals up to 8 years postimplantation. We measured the improvement in performance of speech understanding tests in younger implanted children and compared it with the results of those implanted at a later age. We also used a binary partitioning algorithm to divide the data systematically at all ages at implant to determine the optimum split, i.e., to determine the age at implant which best separates performance of early implanted versus later implanted children. We observed distinct age-of-implant cutoffs, and will discuss whether these really represent critical periods during development. © 2005 Wiley Periodicals, Inc.* Dev Psychobiol 46: 252–261, 2005.

Keywords: *cochlear implantation; plasticity; deaf children; critical period; neurosensory development; auditory function*

INTRODUCTION

The terms ‘‘critical period,’’ ‘‘sensitive period,’’ and ‘‘age-related plasticity’’ are commonly used in describing various aspects of neurosensory development. In a sense, these three terms represent a gradation of effects. The term ‘‘critical period’’ implies a rather fixed time window of opportunity for change while ‘‘sensitive period’’ and ‘‘age-related plasticity’’ describe less abrupt transitions for the plasticity of the system. A wide variety of both human and nonhuman studies investigating developmental aspects of sensory function have generally shown that the plasticity of neurosensory pathways is greater during early development than in the mature subject. These experimental observations include behavioral, physiological, and anatomical studies, and all point to the general notion of an age-related developmental plasticity.

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Basic physiological studies in animals can provide a cleaner picture regarding age-related plasticity than can human studies. This is because animal experiments allow specific features or components of sensory systems to be independently probed. However, the problem is how to relate these findings to more complex behavior and to extrapolate to the human condition. On the other hand, an exploration of age-related plasticity in human developmental research has at least two major drawbacks. First, behavioral responses are the result of complex, multicomponent processes, each of which may have a differing developmental dynamic. For example, in addition to a purely sensory mechanism, a psychophysical task will involve attention, memory storage, and recall as well as motor activity, each of which may develop on separate timelines. Even the use of objective measures in humans, such as electrophysiology or functional brain imaging, does not avoid the problem of dissecting out contributions from the multiple sources that give rise to the collected data.

The second major problem in assessing development of human sensory function, at least psychophysically, is that there are very few (if any) psychophysical tasks or behavioral tests that can be applied to a wide age range of infants and children. Thus, in any longitudinal study there is most often some changing test procedures as subjects ‘‘top-out’’ in earlier, more simple tests. Furthermore, even the same test given to children of different ages may be not be psychologically equivalent because subjects may understand the instructions, strategize, and attend to various cues differently. Thus, attempting to test specific sensory ability in a population ranging in age from babies at 1 year to young adolescents is difficult.

The main focus of this article concerns the early development of human auditory function, as revealed by various behavioral measures of auditory function and speech understanding. The experimental subjects are children who are congenitally deaf (severe to profound hearing loss from birth) and who have been provided with a cochlear implant at various ages. Studies of hearing in children with cochlear implants is an ideal opportunity to explore age-related plasticity or critical periods in auditory development. The deaf-from-birth child will receive a cochlear implant at a particular age, at which point their hearing is essentially ‘‘turned on.’’ In the congenitally deaf population, the ‘‘age at implant’’ is equal to the ‘‘duration of deafness.’’ Additionally, it should be noted that while this group is referred to as deaf from birth, in reality their hearing loss exists prenatally such that their in-utero hearing experience also is diminished.

Many cochlear implant research groups, including our own, have taken the opportunity to monitor various aspects of hearing development in implanted children, and to compare the performance of those implanted at an early age with those ‘‘turned on’’ much later. These studies will be reviewed in some detail and discussed in relation to some of the aforementioned difficulties of interpretation of such human developmental data. First, we present a short background on the evidence for age-related plasticity in hearing development, followed by our more specific human developmental data based on outcome measures in children with cochlear implants.

Basic Science Experiments on Age-Related Plasticity in the Auditory System

By way of introduction, we review here some basic science evidence for age-related plasticity in the auditory system. Over the past few decades, many studies have shown that the central auditory brain develops under the influence of neural excitation patterns from the ears. In other words, peripheral activity patterns promote the early development and the maintenance of the central systems. The functions of the periphery and central components are intimately linked, and this is most evident during an early developmental period. It is appropriate, first, to mention two pioneering studies which drew attention to the notion that early sensory input has a critical role in central brain development. These experiments paved the way for many modern studies on age-related brain plasticity. The seminal study was in the developing chick auditory system by Levi-Montalcini (1949), who reported on the anatomical changes to central auditory pathways after the otocyst of the chick embryo was removed or damaged. Later, and perhaps most famously, Weisel and Hubel (1963, 1965) showed that visual cortical wiring responsible for ocular dominance columns is disrupted in cats if, during a ‘‘critical’’ early postnatal period, it has had visual input from one eye only (i.e., after neonatal monocular deprivation).

These seminal experiments were followed by others in most of the sensory pathways. For example, studies in the somatosensory system revealed a reorganization of somatosensory maps in cortex after damage or partial deafferentation of the sensory inputs. This was demonstrated, for example, after whisker removal in young rodents (Waite & Taylor, 1978) and after peripheral nerve damage or digit removal in both developing and adult animals (Kaas, Merzenich, & Killackey, 1983; Merzenich et al., 1984; Rasmusson, 1982). A typical experimental finding, in the somatosensory system, was that after digit amputation or deafferentation, the areas of somatosensory cortex originally coding the dennervated skin region became rewired so as to code the sensory input from adjacent areas. In some ways, one could describe the effects as being a cortical overrepresentation of skin areas adjacent to the site of lesioning. These studies generally revealed considerably more neural reorganization resulting from experimental manipulations in the neonatal subject compared with similar manipulations in the adult animal.

In the auditory system, many studies have revealed some of the neuroanatomical changes that result from ablation of one cochlea in the very young animal. These changes include loss, or pathological change, to neurons in brainstem and midbrain (Hashisaki & Rubel, 1989; Moore, 1994; Moore & Kitzes, 1985) and, in some cases, the formation of novel innervation patterns in the brainstem and midbrain pathways (Kitzes, 1984, 1996). Is there evidence of critical periods? In studies investigating connections to inferior colliculus (Clopton & Silverman, 1977) in the cat, after a unilateral cochlear lesion there was no effect in cats older than 60 days. In mice (Webster, 1983) a unilateral cochlear lesion altered cell size in the cochlear nucleus and in other brainstem areas only if induced before 24 days of age.

Another well-documented set of research findings on auditory-system plasticity relates to the cochleotopic or tonotopic representations within the auditory pathway, and how these can be modified by experimental manipulations of sensory input. These effects were analogous to findings in somatosensory cortex after peripheral dennervation studies (as outlined earlier). Thus, Robertson & Irvine (1989) reported on reorganization of cortical tonotopic maps after cochlear lesions were made in the adult animal. These authors showed that after well-defined lesions to the cochlear sensory epithelium, the areas of auditory cortex that were tonotopically corresponding to the areas of deafferentation now contained neurons ‘‘wired up’’ or tuned to cochlear frequency regions adjacent to the experimentally lesioned area. In similar experiments but ones in which cochlear lesions were made in neonatal animals, the reorganization of cortical tonotopic maps was found to be much more extensive (Harrison, Nagasawa, Smith, Stanton, & Mount, 1991). In another study by Harrison (2001), the difference between adult plasticity and that of the developing subject was even more apparent at the level of the auditory midbrain (inferior colliculus). At this level, tonotopic map plasticity is evident only during an early developmental period (in chinchillas, within a few weeks of birth), but not in the adult animal. Taken together, these studies clearly show that the mainline organization of the auditory system (i.e., its tonotopic projections) is more plastic during early development, and less so in the mature subject.

In animal studies more related to cochlear implantation, congenitally deaf white cats showed developmental plasticity (at the level of auditory cortex) only if they received stimulation with a cochlear implant prior to 6 months of age (Kral, Hartmann, Tillein, Heid, & Klinke, 2001). All of these basic physiological studies, taken together, indicate that the auditory system has considerable age-related plasticity.

Age-Related Plasticity in the Human Auditory System

We now turn from animal model experiments of auditory development to studies in human subjects specifically related to the effects of cochlear implantation. Cochlear implants are devices that ultimately send electrical pulses to the cochlea and stimulate the auditory nerve in children and adults who have severe to profound sensorineural hearing loss. The electrode-stimulation pattern is closely related to environmental acoustic signals, with a particular emphasis on coding the information contained in speech sounds. The patterns of electrically evoked activity induced in the auditory nerve are transmitted to various regions of auditory cortex for the perception and the understanding of sounds, speech sounds in particular. It is not clear how the duration of auditory deprivation before implantation impacts on the development of central auditory pathways. There are a number of developmental processes taking place at this time such as myelination, dendritic pruning, and axonal growth. These intrinsic processes may continue without environmental stimulation, but at some stage, for normal development, peripheral input is required. The ability of the human system to develop and adapt to the novel stimulation delivered by a cochlear implant still requires further study. Specifically, we asked, ‘‘Can these pathways change in response to chronic stimulation? If the system does show plasticity, is it limited by the age at implantation (i.e., the duration of auditory deprivation)?’’

In children with pre- or perilingual onset of deafness, the cochlear implant should ideally provide sufficient information to allow for development of oral speech and language skills. Although there are nonlinguistic benefits to hearing with a cochlear implant such as improvements in quality of life, enjoyment of music, and environmental awareness, the outcomes that have most commonly been monitored are behavioral measures of speech and language perception and production.

We report here two of our own studies, specifically our attempt to determine if there is evidence for specific critical periods during development.

SPEECH PERCEPTION OUTCOMES BY AGE AT IMPLANT: STUDY 1

In the first study, subjects were 82 children (43 female, 39 male) with severe to profound hearing loss from birth. All children attended the Cochlear Implant Program at The Hospital for Sick Children (Toronto) and had used their implants for a minimum of 5 years (range = 63–163, mean = 97.2 months postimplant). All children received similar Nucleus cochlear implant devices at ages ranging from 2 to 13 years (range = 2.0–13.3, mean = 5.4 years).

Outcome measures were collected prospectively. Measures assessed were standard speech-perception evaluations forming part of the routine battery of tests used in the program. Reported here are results from a closed-set task, the Test of Auditory Comprehension (TAC; Office of the Los Angeles County Superintendent of Schools, 1976), and from open-set tasks including the Glendonald Auditory Screening Procedure (GASP; Erber, 1982) and Phonetically Balanced Kindergarten Word List (PBK; Haskin, 1949), for which both phoneme and word scores are presented.

The children were grouped into subsets by age at implant (2 years, $n = 14$; 3 years, $n = 16$; 4 years, $n = 14$; 5 years, $n = 15$; 6 years, $n = 1$; 7 years, $n = 2$; 8 years, $n = 6$; 9 years, $n = 5$; 10–13 years, $n = 7$) and were followed up to 8 years postimplant. In this dataset, the number of subjects implanted at age 6 and 7 years ($n = 3$) is too small to be representative and therefore have been omitted from some of the following analyses. Measures of speech perception were recorded pre-implant and at regular intervals postimplant (6, 12, 18, and 24 months and annually thereafter). Ideally, all patients should have the same number of follow-up outcome measures at any point in time; however, this has not been achieved because of missed appointments and other practical constraints. On each of the outcomes, only those patients with more than two data points are included. Results are presented as mean test values; any time point with only a single-patient result was omitted. Pre-implant and first-year postimplant results are missing for the younger age groups in several tests as the tasks were not age appropriate. For test results at age 6, where a one-way ANOVA indicated significant difference among means, multiple comparison testing was conducted comparing the older three groups to the 2-year-old group (control).

Results

In Figure 1, mean TAC scores before and at various time intervals after implant are plotted for each age of implant group as indicated by the symbol key (right). To remind the reader, this grouping could equally be labeled "duration of auditory deprivation" given that the subjects are congenitally deaf. After about 60 months postimplant, the children implanted at 5 years of age or younger (i.e., short duration of deprivation; filled symbols) score higher than the older age at implant groups. For all age-at-implant groups, a point in time is reached after which gains are limited or absent. This plateau is at a lower TAC score for the children with longer duration of deafness. However, the differences between age-at-implant groups are not as pronounced as in the open-set tests reported next. Unlike the other tests reported here, the TAC is essentially a battery of increasingly difficult auditory/speech discrimination tasks. On the surface, this one "test" can be applied to children of different age groups in a longitudinal study; however, in reality this is a battery of tests progressively measuring increasingly complex aspects of speech perception. This type of test battery does not measure any specific aspect of speech perception.

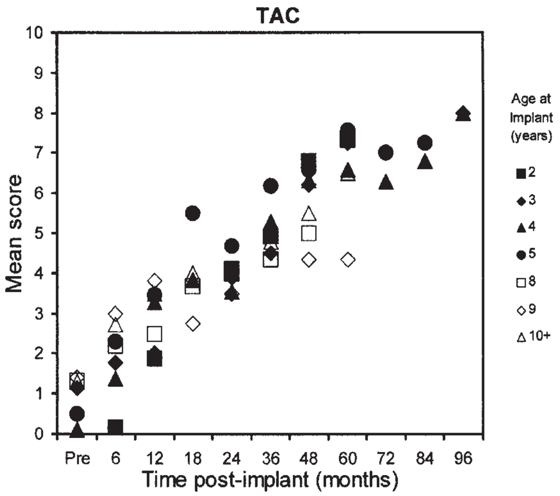

FIGURE 1 Performance, over time, of congenitally deaf children provided with a cochlear implant at different ages (symbols key, right). Shown here are mean scores in the Test of Auditory Comprehension (TAC). Pre-implantation scores are shown to the left on the abscissa.

Figures 2–4 show data from three open-set tests, PBK phoneme, PBK word, and GASP word, respectively. Mean scores for pre- and postimplantation are shown for

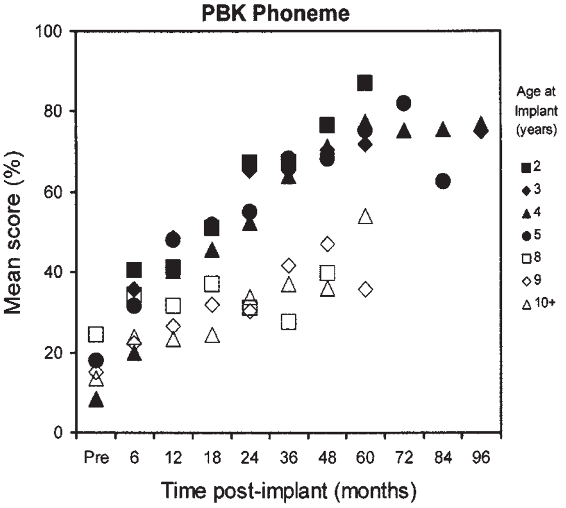

FIGURE 2 Scores in the PBK phoneme test, pre-implantation (far left) and at intervals post-implantation. Mean values are shown for each age at implant group, as indicated by the symbols key (right). Open symbols represent scores for children who had a long duration of deafness before implantation at age 8 or older.

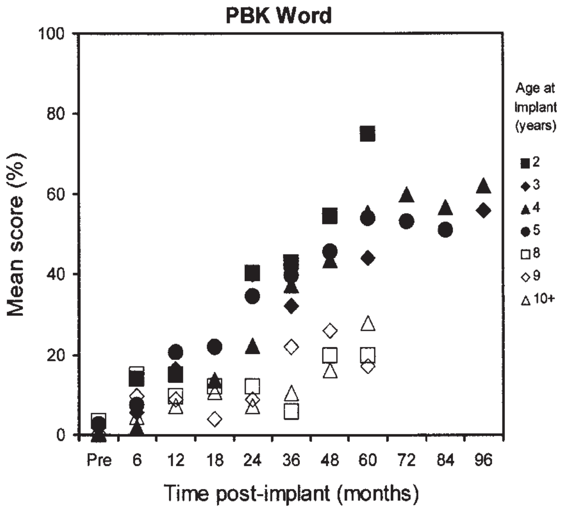

FIGURE 3 Scores in the PBK word test for deaf children before a cochlear implant (far left) and at intervals postimplantation. Mean values are shown for each age at implant group, as indicated by the symbols key (right).

each age at implant/duration of deprivation group. In all tasks, the children implanted at 2 years of age (filled-square symbols) achieve higher scores than other age groups at 60 months postimplant. The longer hearing deprived groups, implanted at age 8 years of age or later (open symbols) clearly show less rapid improvement in performance over time after cochlear implantation (i.e., the slope of the performance data, over time, is less steep). To put into perspective the performance of these children with cochlear implants, in all of these open-set tests (Figures 2–4), normal-hearing children would score at the 100% level.

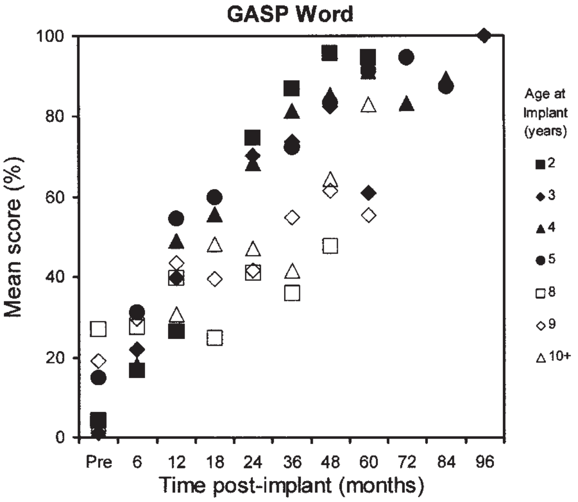

FIGURE 4 Mean scores in the GASP word test, pre- and postimplantation, for each age at implant group as indicated by the symbols key (right).

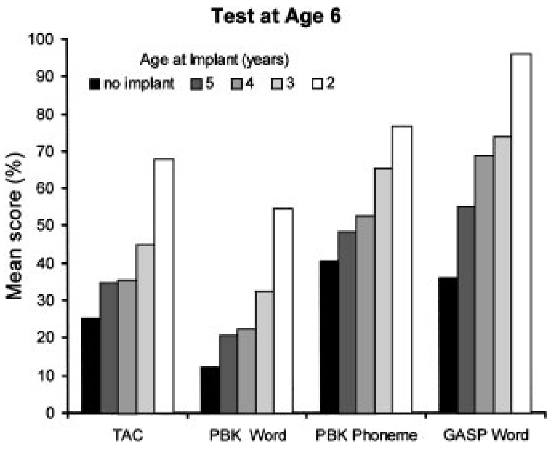

FIGURE 5 Speech perception outcome results at age 6 years. Results from four tests are shown: TAC, PBK word; PBK phoneme, and GASP word. The mean score (%) for congenitally deaf children, at 6 years of age who have not yet received an implant is shown (black bar), and who had a cochlear implant device implantation at ages 2, 3, 4, or 5 years of age (see key).

Another way of presenting these data is to plot age-at-test results, which show how the duration of implant use impacts test results in children of the same age. In Figure 5, the mean score for each test made when the child is 6 years of age is plotted for the nonimplanted child versus those having implants at the ages of 2, 3, 4, or 5 years. Children implanted at 2 or 3 years of age consistently achieve higher test scores than those implanted at later ages.

These speech perception outcomes indicate that after long-term implant use, children implanted at young ages perform better than those implanted at older ages. By 60 months postimplant, children implanted at 5 years of age and younger outperformed their older peers in all phoneme and word speech perception tasks; children implanted at 2 years of age appeared to exceed all other age groups. Even with long periods of implant use, children implanted older may not achieve levels obtained by those implanted younger.

One question still remains: "Is there a clear critical period during which cochlear implantation provides a clearly superior performance?"

SPEECH PERCEPTION OUTCOMES BY AGE AT IMPLANT: STUDY 2

In the second study, we used an objective method to split datasets on the basis of age at implantation (equals duration of deafness) to compare average performance of children implanted before and after that age. In this study, subjects were 82 children (41 female, 41 male) aged 1.9 to 15.4 years (mean = 6.3 years) at implantation. All children had severe to profound prelingual hearing loss, the majority having congenital onset. Subjects were followed for up to 5 years postimplant (El-Hakim, Abdolell, Mount, Papsin, & Harrison, 2002).

Binary partitioning analysis splits the datasets at all possible ages of implantation and reports the optimal split age (Abdolell, LeBlanc, Stephens, & Harrison, 2002). In short, a binary partitioning algorithm was set up to determine an optimal age at implantation cutoff that best separates the subjects according to the outcome measure into younger versus older age groups. The data in every outcome measure is sorted by the age variable, and a sequence of splits defined at unique age values is performed. For each split, the data is partitioned into two groups: Those subjects whose age is below that value form one group, and those whose age is greater than or equal to that value form the other group. Splitting of the data is a procedure based on the concept of reducing heterogeneity in the response distribution by separating the subjects into two subsets based on ages that are more homogeneous when they are split than when they are combined. A measure of heterogeneity is deviance, and the maximum drop in deviance identifies the optimal split which is the age cutoff that best separates the age groups. In other words, this method objectively compares the rates of improvement in test outcomes for children implanted at various ages and can define an age of implant (duration of deafness) at which outcome auditory test performance is markedly altered.

Results

Figure 6 shows the results of binary partition analysis for PBK word test scores of 69 children postimplantation. The raw data is plotted in the upper left panel (These are essentially the same data as plotted in Figure 3.) The right-hand panel shows the goodness of split (%drop in deviance) for each age at implantation. The best split, as

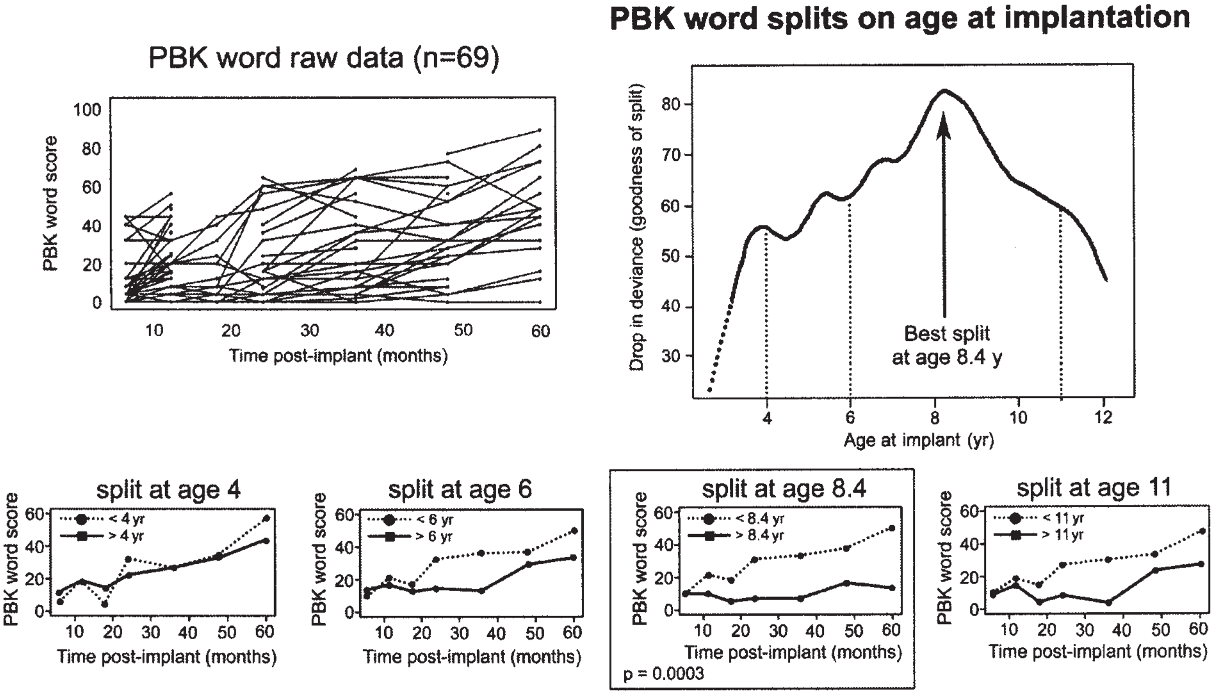

FIGURE 6 The use of binary partitioning to determine what age of implantation, if any, best separates the performance of children with the device. Here, the outcome is assessed using the PBK word test. Raw data are illustrated in the upper left-hand panel, in which PBK word scores are plotted as a function of time postimplantation for 69 children implanted at different ages. The data are systematically partitioned to compare younger implanted children with those implanted at an older age. The upper right-hand panel shows the outcome of this binary partitioning analysis. The drop-in deviance (goodness of split) is plotted for all possible divisions of the data based on age at implantation. Here, the optimal split is at age 8.4 years. The average improvement in performance of children implanted before age 8.4 years versus after is plotted in the boxed (third from left) lower panel, together with similar plots at other (nonoptimal) age splits.

indicated by the arrow symbol, is at age at implant of 8.4 years. In the lower panels, the average PBK word score, over time postimplant, is plotted for the best split at age 8.4 years (boxed graph) as well as for less optimal age of implantation splits (at 4, 6, and 11 years of age). For the optimal split, the average progress in the PBK word test is significantly better in children implanted at the younger age ($p = 0.003$). In more general terms, note that the slope of test result improvement, over time, for children implanted before age 8.4 years (a sensory deprivation of 8.4 years) is much different from that found for children implanted later and thus having longer durations of deafness. The binary partitioning analysis simple tells us that it is at age of implant (or duration of deprivation) of 8.4 years when the outcomes are maximally different.

The plots in Figures 7 and 8 show ‘‘goodness of split’’ versus age at implantation for GASP word and TAC scores, respectively. The average performance of children implanted below and above the optimum age-of-implant split is shown by the dashed and continuous curves of the lower plots. For the GASP word data (Figure 7), the optimal split is at an age of implant of 5.6 years. For the TAC test (Figure 8), it is at 4.4 years.

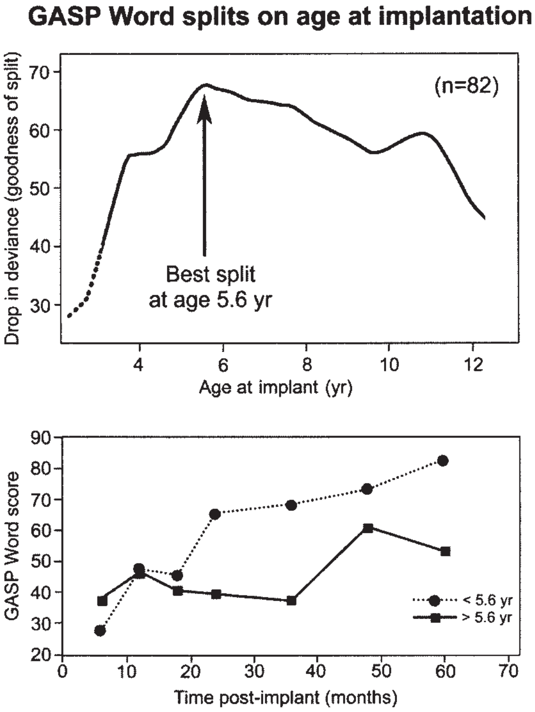

FIGURE 7 Binary partitioning outcome for GASP word test; analysis based on data from 82 children. The optimal split of data is at age at implant of 5.6 years. The lower panel shows the average progression in performance in children implanted before (dashed line) and after (continuous line) age 5.6 years.

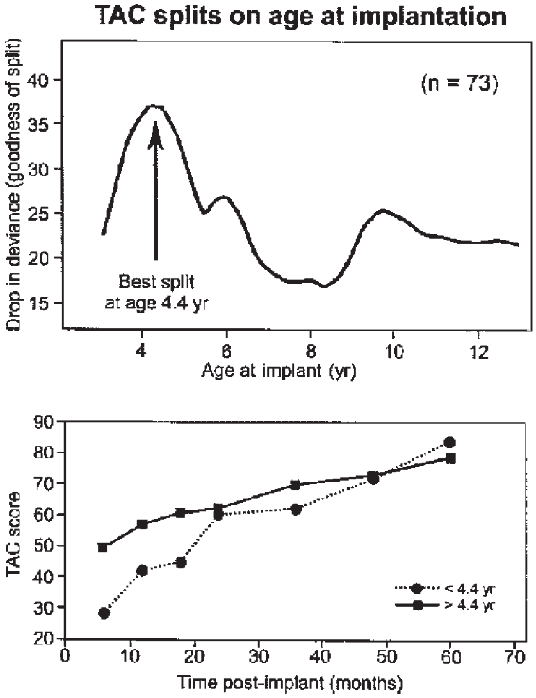

FIGURE 8 Performance in TAC tests postimplantation in 73 children. The binary partitioning result is shown in the upper panel. Optimal data split is at age at implantation of 4.4 years. The lower panel shows average change in performance of children implanted younger than 4.4 (dashed lines) versus those implanted at a later age (continuous lines).

DISCUSSION

First, we will briefly discuss the present data regarding how they inform us about age-related auditory system plasticity and possible critical periods of development. We will then discuss, more broadly, critical periods in human sensory development and practical reasons for knowing about them, if they do exist. Part of that discussion relates to the advantages and the problems in using ‘‘natural experiments,’’ such as these involving deaf children with cochlear implants, to study critical periods in humans.

The Present Study

Our general findings reported here are in line with other studies which suggest that speech understanding outcomes are related to age at implantation, or duration of auditory deprivation (Dawson et al., 1992; El-Hakim et al., 2002; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Gibson, Herridge, & Rennie, 1997; Lesinski, Battmer, Bertram, & Lenarz, 1997; Nikolopoulos, O’Donoghue, & Archbold, 1999; Snik, Makhdoum, Vermeulen, Brokx, & van den Broek, 1997; Tyler et al., 1997).

Some authors have declared, based on their data, that there is a critical period in development during which oral communication must be audible for normal speech and language development (Brackett & Zara, 1998; Ito, Suzuki, Toma, Shiroma, & Kaga, 2002; Robinson, 1998) and that central auditory plasticity is limited for children implanted at older ages (Manrique et al., 1999). We find a clear distinction between postimplant performance in children having a duration of deprivation of up to 6 years compared with those deaf until implanted at age 8 years and older. These differences are well illustrated in Figures 1–4 and in the ''test at age 6'' outcomes of Figure 5; however, our attempts to use binary partition analysis to seek one specific break in the data was not successful. What we find is that the break in the data is at a different age of implant depending on the test used. There is no universal age or critical period.

We observe that the optimal age of implantation split is low for tests which involve some simple tasks; thus, for the TAC data (Figure 8), the best split is at age of implant (duration of deprivation) of 4.4 years (The closed set, early-stage tests in TAC involve relatively simple sound identification.) More difficult tests (with open-set tasks) such as GASP word and PBK word (Figures 6 and 7) have higher optimum age at implantation splits at 5.6 and 8.4 years, respectively. The importance of our results is that they emphasize that in any investigation of critical periods, or age-related plasticity, both the underlying neurobiology and the testing methods used to make assessments can influence findings. Clearly, when we ask about critical periods in neurosensory development, especially in behavioral human studies, one should take into account the complexity of the outcome-measure task that is being used to assess performance.

Practical Reasons for Learning about Critical Periods

Why are we interested in finding out about critical periods in development? In basic science studies, such information can provide insights into mechanisms of development. For example, it may allow us to correlate some behavioral or physiological process with specific biological events (e.g., a neurotransmitter receptor site expression) or anatomical stage (e.g., synapse formation, axonal myelination). In applied human studies, there is additional importance because the existence of a critical period may influence decisions about clinical intervention. Clinical interventions affect quality of life for individuals, and they also cost money. For example, 20 years ago when cochlear implants were just starting to be provided in Canada, there was a very limited resource. Funding was only available for a select few. Part of the patient-selection process was to decide which individuals would benefit most, and for the congenitally deaf child this involved asking whether there was a certain age over which a cochlear implant was of little benefit. This was the same as asking: ''Is there a critical period for cochlear implantation?''

The issue of deciding on the optimal intervention is not just economic. More importantly, in the habilitation of the deaf child, there are intervention options. Choosing between interventions can have lifelong implications. Do we provide a cochlear implant in an older congenitally deaf child, who might benefit very little, at the expense of having that child learn sign language and perhaps flourish in what is often called the deaf culture? Knowledge about critical or sensitive developmental periods is useful for making informed decisions on these issues.

Cochlear Implant Outcomes as a ''Natural Experiment''

The children in these studies have experienced auditory deprivation for various periods of time before receiving their cochlear implant; however, as a ''natural experiment'' in developmental plasticity, the use of human cochlear implant data does not, of course, provide a clean, clear-cut picture. While all the implanted children had a severe to profound hearing loss from an early age, they were not all totally without hearing. Many had, before implantation, some degree of auditory input because of residual low-frequency hearing prior to cochlear implantation (residual here meaning having high threshold responses in the 0.5- to 1-kHz range, made useful only with high-amplification hearing aids). Some children had hearing-loss onset at birth or just after birth and thus would have experienced some early activation of the auditory system (including hearing in utero).

It also is the case that the restoration of hearing using a cochlear implant is not a full and natural restitution of normal auditory function. The cochlear implant stimulates a limited part of the cochlear nerve array, and can input only a very limited information set compared to normal hearing, with restrictions on both spectral and temporal cues. To emphasize this point, one could note that in the normal ear there are 50,000 channels (i.e., the number of cochlear afferent neurons) to transmit acoustic signals to the brain compared with only 20 cochlear electrode channels of the implant device. The children in these studies only receive an electrode array for one ear, thus clearly lack the normal binaural input and some of the hearing benefits that this allows (e.g., binaural sound localization). Despite this extremely limited acoustic information input, children implanted at an early age do very well, and some approach the speech and language performance of an average, normally hearing child. This says much about the redundancy in the normal auditory system. We do not actually need 50,000 frequency channels; telephone voice coding (vocoder) studies indicate that 10 to 12 are sufficient to transmit speech information. The performance of the younger implanted child also speaks to the high degree of plasticity inherent in the developing auditory system.

Cochlear Implants in Adults Versus Infants. There is another important concept to consider in interpreting these cochlear implant data. In subjects who become deaf after normal auditory system development (e.g., as adults, or at least postlingually) and who receive a cochlear implant with only a short delay, performance appears to depends on how well the device can emulate the lost cochlear mechanisms, i.e., how close the novel sound percepts are to what the subject was familiar with. In the congenitally deaf infant, there is no such ‘‘reference,’’ no memory of previous hearing experience. In fact, with a cochlear implant provided at a very early age, the stimulation by the implant electrodes is likely to be the driving force for auditory brain development, and the percept that is established becomes ‘‘normal’’ for that individual. In other words, the neural activity patterns caused by electrode-array activation take the place of environmental acoustic stimulation and influence the overall development of hearing. Because of that likelihood, an important potential problem for the future will relate to the consequences of ‘‘upgrading’’ or replacement of cochlear implant devices. Drastic changes to the electrode-array characteristics (e.g., number of channels; repositioning within the cochlea) or the speech-processing strategy which assigns acoustic information to electrodes could result in a new mismatch between the novel information patterns and processing mechanisms that the brain had developed based on the original implant device.

An important general notion is that at one end of a developmental time scale, in the mature auditory system, cochlear implants will have an effect by modifying existing neural networks—a true reorganization. In the early developing brain, the electrode-stimulation patterns will be driving neural organization for the first time. Intervention with a cochlear implant at any time during development will involve a mixture of organization and reorganization. We could suggest that any ‘‘intervention’’ will produce changes to previously existing neural networks as well as promotion of new pathways, and that the ratio of these effects will depend on developmental age.

CONCLUSION

Our initial question was whether there is a ‘‘critical period’’ in relation to intervention (with a cochlear implant) in the congenitally deaf child. Using a strict definition of the term and asking if there is one certain period of deafness after which a cochlear implant is of little or no value, the answer is no. Within this article, we have discussed various reasons why it is unlikely one critical period could exist, not the least of which is because the measured behavioral outcome is the result of many mechanisms, each with a differing developmental dynamic. We also have demonstrated that the outcome measurement tool will impose its own bias. If we ask whether there is an age-related plasticity effect, then absolutely the answer is yes. Our own data and that of others have clearly demonstrated that cochlear implant intervention at an early age in the congenitally deaf infant results in significantly better outcomes in speech understanding and language development.

NOTES

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