Neuropsychological Research Approaches to the Study of Central Auditory Processing

Paula Tallal

It is obvious from observing deaf children that dysfunction in the sensory registration of the auditory signal is sufficient to disrupt speech perception and give rise to a language disorder. However, full processing of the acoustic signal goes far beyond the level of peripheral sensation. Whether deficits might arise in these higher level stages of auditory processing which are sufficient to disrupt speech perception and hence interfere with normal language development is a question which has stimulated much research and continues to be highly controversial. However, knowing as we do, the devastating effects of impairment of auditory sensation on the subsequent oral language development of hearing impaired children, it seems imperative that we take seriously the mounting evidence of auditory perceptual impairments in children with language disabilities.

Stages of Central Auditory Processing

In an attempt to investigate whether impaired auditory perceptual mechanisms may be implicated in some developmental language disorders, research has focused on investigation of those higher level auditory perceptual processes that may be most directly involved in speech perception. But what is central auditory processing (CAP)? Simply put, once a signal is detected, what subsequent stages of processing must be completed in order for the signal to be thoroughly perceived? Once a signal is detected, it is of further use only if it can be related to other signals. Thus, once a subject can detect that a signal has occurred, it is important to detect when two, rather than one, events have taken place. The ability to detect two stimuli versus one continuous event is a function called temporal resolution. Temporal resolution pertains to the time necessary between the offset of one stimulus and the onset of a second stimulus to determine that two discrete stimuli (rather than one continuous event) have occurred. Once two stimuli have been detected, it is important to determine whether they are the same or different stimuli. Acoustic signals may differ along the dimensions of frequency, amplitude, and time. If two stimuli are determined to be different, additional information can be derived by determining the temporal order or sequence in which they occurred. The ability to make this temporal order judgement will also be affected by the extent to which the two stimuli differ in frequency, amplitude, and duration and also the interval between the offset of the first stimulus and the onset of the second stimulus (inter-stimulus-interval, ISI). Once two stimuli have been detected and it has been determined that they are different and the subject can perceive temporal order of their occurrence, additional stimuli can be processed in the same manner. However, as additional stimuli are processed, each must be stored in short-term memory in order for them to be combined or recalled.

Paula Tallal, Ph.D.
Department of Psychiatry
University of California, San Diego
La Jolla, California

Evaluating CAP in Language Impaired Children

These basic components of perception (detection, temporal resolution, discrimination, sequencing, and serial memory) have been investigated in language impaired children. As a definition of specific developmental language impairment excludes sensory hearing loss, it is not surprising that research has shown that these children have normal detection abilities. Similarly, several research studies have shown these children to have normal auditory temporal resolution functions. However, several authors have demonstrated that language impaired children are significantly impaired in their ability to perceive the temporal order or sequence of acoustic events. Lowe & Campbell (1965) showed that the same aphasic children who were unimpaired in auditory temporal resolution tasks were markedly impaired in their ability to indicate which of two tones occurred first when they were presented in rapid sequence. This finding of impaired nonverbal auditory sequencing in language impaired children has been replicated experimentally by several other investigators using a variety of different stimuli and subjects. It is generally concluded that impaired temporal order perception might be a major factor in the communication difficulties of aphasic children.

Interestingly, it has also been noted that children with specific developmental reading disorders (dyslexia) are also impaired in their sequential processing abilities. Doehring (1968) found that deficits of sequential processing in reading impaired children were particularly marked when items to be sequenced were presented rapidly, a finding that has also been noted with language impaired children and reading impaired children by Tallal (1980). These similarities in the pattern of perceptual dysfunction of children with developmental language and developmental reading disabilities is of particular interest in light of more recent reports that perhaps the largest subgroup of developmentally dyslexic children have concomitant oral deficits.

Research from many studies leaves little doubt that language impaired children as a group consistently show deficits in their ability to perceive the temporal order or sequence of nonverbal acoustic events. However, it has not been possible to determine whether a defect in sequencing is a primary impairment in some communication disorders, is specific to the auditory modality, or is positively correlated with the degree and type of communication impairment. Furthermore, the precise relationship, if any, of these nonverbal auditory sequencing deficits to speech and language perception cannot be established from the published studies.

An important methodological difficulty common to all of the experiments investigating sequencing was the failure to show that subjects were able to discriminate accurately between stimulus elements which were combined and presented in sequence. It had been assumed that, because discrimination between stimulus elements presented in isolation was demonstrated, deficits in perception of sequences composed of these elements must result from a failure to perceive or remember temporal order. However, as early as 1959, Hirsh pointed out that, in order to perceive the sequence of a two-element stimulus pair, one must first perceive that the two elements are separate rather than fused and then decide whether they are the same or different. Nevertheless, in experiments designed to assess sequencing and memory abilities of language delayed children, no steps were taken to show that subjects could perform the discrimination task. Thus, it is possible that failures were due to difficulty in discrimination between the two stimuli presented sequentially, even though subjects had no difficulty discriminating between the stimuli when they were presented singly. If this were the case, then poor performance on tests of perception of temporal order could be attributed to difficulty in discrimination between the items of a stimulus pair, rather than in determining their temporal order. Such a difference would markedly change the theoretical interpretation pertaining to the interrelationship between auditory perceptual and speech perceptual deficits.

In order to understand the relationship between basic perceptual disorders and language delay, it seemed to be necessary to move away from the previously used experimental procedures and to re-evaluate the experimental questions. A new experimental method and stimuli seemed to be required. A means of generating nonverbal stimuli that imitated the acoustic properties of speech sounds but did not match the acoustic spectrum of any specific speech sound was needed. Such signals could be acoustically speech-like, but at the same time, linguistically meaningless. Recent work in the field of psychoacoustics, together with the development of computerized speech synthesizers, have made it possible to specify and control the critical acoustic features necessary for such signals.

In order to understand the perceptual deficits of children with language delay, it was also essential to devise a method which would enable the children to report in detail exactly what they perceived in each stimulus presentation in a nonverbal manner, furthermore; it was important that the method should be easy to demonstrate without the need for verbal instructions or verbal response. The method also needed to be flexible enough to allow for several different aspects of perception to be investigated systematically by changing only one variable at a time. It was also important to assure that the results obtained in perceptual studies using nonverbal complex acoustic stimuli could be compared directly to the results of similar studies using nonverbal visual stimuli or verbal stimuli. Furthermore, studies of the relationship between these perceptual abilities and other abilities such as language comprehension and speech production were needed.

Studies with Repetition Method

In all of our experiments, a nonverbal operantly conditioned method designed specifically for these studies was used. This method has come to be called the Repetition Method. In brief, subjects are presented with a single stimulus (stimulus 1) and trained to respond to ("repeat") this stimulus by pressing one of two panels on a response box. Next, a second stimulus (which was chosen to differ from stimulus 1 in very specific ways in various experiments) is presented. Subjects are trained to respond by pressing the other panel on the response box. Once subjects have been trained to a very high level of performance to press panel 1 for stimulus 1 and panel 2 for stimulus 2, more than one stimulus can be presented in sequential order.

Using the repetition procedure paired with a second procedure (same — different) in which subjects are trained to press one panel) on the response box for two stimuli that are the same and the other panel for two stimuli that are different, each component of perception can be investigated in systematic hierarchical fashion. By carefully selecting stimulus 1 and stimulus 2 so that they differ from each other by only a single variable, differences among auditory, visual, and cross-model perception can be evaluated systematically for each of the components of perception. Similarly, nonverbal and verbal perception can be compared. Finally, these components of perception can be evaluated using a variety of speech sound contrasts that are specifically selected to differ by only a single acoustic feature. In our first series of studies, the same group of 12 carefully selected children with specific developmental language delay and 12 normal matched control children participated as subjects. In subsequent studies, 35 language delayed children between the ages of five and nine years and matched controls participated. The criteria for inclusion as language delayed or normal and a detailed clinical descripton of these subjects have been given in previous publications.

Tallal & Piercy (1973a) demonstrated that language delayed children were impaired in their ability to perceive the temporal-sequence of rapidly presented auditory nonverbal signals. However, it was also found that these children had equal difficulty in discriminating between the two tones in the stimulus pair when they were presented.

rapidly. Thus, the sequencing deficit was the result of a more primary discrimination deficit of rapidly presented stimuli. Clearly, if one cannot discriminate between two stimuli, then one will not be able to determine the order in which they occured. This deficit was demonstrated by systematically varying the duration of the intersound interval (ISI) between two complex nonverbal tones of constant duration presented in sequence.

In a second experiment (Tallal & Piercy, 1973b), the same language disordered subjects and control subjects were tested for their ability to perceive other sequences of nonverbal stimuli in the auditory and visual modalities. Performance was studied as a function of the duration of stimulus elements, the interval between elements, and the number of elements in a sequence. The results of this study showed that there were no significant differences between the two groups on any of the visual tests. On the auditory tests, however, the language impaired subjects, but not the controls, were adversely affected by a decrease in the duration of the stimulus elements, by a decrease in the interval between elements, and by an increase in the number of elements. Further analysis showed that the total duration of the stimulus patterns was highly correlated with the performance of these children. These same children could respond to two and three element sequences correctly at slower rates of presentation, but were unable to respond correctly to the same nonverbal stimuli when they were presented at more rapid rates. It was suggested that children with developmental language delay are incapable of responding correctly to acoustic information that is presented at rapid rates and that it is possible that this auditory perceptual impairment may underlie their language impairment.

How could such a defect in processing rapidly changing acoustic information actually affect the speech perception abilities of these children? Recent work in speech synthesis and perception has shown that vowels and certain consonants are processed differently by normal listeners. Interestingly, these differences in speech perception by normal listeners can be attributed to the differential duration of the critical acoustic information which characterizes these two classes of speech sounds. Liberman et al. (1967) have shown that, for the stop consonants, there appears to be a relatively complex relationship between the speech sound and its acoustic representation. The essential acoustic cue for such signals is the rapidly changing spectral transitions that characterize the onset of the signal. These cues are not only transitional in character, but also are of a relatively short duration, approximately 50 ms. In contrast, the major acoustic cues for vowels are steady state frequencies. They have a relatively long duration, approximately 250 ms, and remain constant over the entire duration of the stimulus.

The results of our previous experiments demonstrated that, unlike normals, children with developmental language delay were unable to respond correctly to non verbal stimuli presented at rapid rates. On the other hand, they responded adequately to the same stimuli at slower rates of presentation. Based on these findings, we could predict that language impaired children would be unimpaired in discriminating speech stimuli that did not require them to process rapidly changing acoustic cues. Thus, we predicted that they would be unimpaired in discriminating between steady state vowels. However, we predicted that these same children would show impaired discrimination of synthesized stop consonants, such as /ba/ and /da/, that have the same total duration as the vowel stimuli, but also have an initial transitional component of only 40 ms. Recall that this initial transitional component is critical for discrimination of consonants.

The same subjects and procedures (the Repetition Method) as were used in the previous experiments were used again in this series of experiments. However, in these experiments the ability of language impaired children to discriminate verbal stimuli rather than nonberbal stimuli was investigated. Furthermore, the acoustic cues necessary for discrimination between speech stimuli were manipulated to determine the extent to which inability to process rapid acoustic change might characterize the speech perceptual abilities of language impaired children. The results of the study demonstrated that the language impaired subjects were unimpaired in their ability to discriminate the steady state vowel stimuli (Tallal & Piercy, 1974). Their performance did not differ significantly from their own previous performance using nonverbal auditory stimuli of the same duration on any of the perceptual or serial memory tasks studied. Clearly, their performance did not deteriorate merely as a consequence of changing from nonverbal to verbal auditory stimuli, when both are of equal duration and of a steady state character. However, the results with synthesized stop consonants were entirely different. The language delayed subjects discrimination of consonant stimuli was significantly inferior to both their own discrimination of vowel and nonverbal stimuli and that of their matched controls. A further experiment by Tallal and Piercy (1974) showed that the limiting factor underlying the inferior performance of these language delayed children on the consonant task was indeed the duration of the rapidly changing initial portion of the acoustic spectrum for consonants. In these experiments, a speech synthesizer was used to extend the initial transitional acoustic component from 40-80 ms within the same consonant stimuli. The ability of language disordered children to discriminate between consonants which incorporate longer duration transitions was found to be unimpaired. In contrast to the previous experiment in which only two of the 12 langauge delayed children responded adequately to the consonant syllables with 40 ms duration transitions, all 12 children responded correctly to the same syllables with the extended duration transitions. It is important to note that the normal children still perceived these extended duration consonants as the intended syllables /ba/ and /da/.

If the primary cause of the observed language disorder of some language delayed children is a failure to perceive certain speech sounds, then it would seem that these same speech sounds would be produced incorrectly or omitted in their speech. Our studies of this concept (Tallal, Stark, & Curtiss, 1976) suggest that the speech production abilities of dysphasic children mirror their speech perceptual abilities. That is, those speech sounds characteristically incorporated in rapidly changing transitions which are critical for their perception are most difficult for dysphasic children to perceive, and are also the speech sounds most often misproduced by these children. This result adds further support to the hypothesis that some developmental language delays result, at least in part, from a primary nonverbal auditory perceptual deficit. This deficit may preclude normal speech perception and production which, in turn, may disrupt the normal development of speech and language.

These findings have now been extended to demonstrate that the perception of syllables in words, as well as ongoing comprehension of language, is highly correlated with the temporal processing abilities of these children. Furthermore, the performance of language impaired children who had no gross neurological hard signs was evaluated on a comprehensive battery of neurological tests for soft signs. The results of the study found the language impaired group to be distinguished by less efficient performance in a number of areas, particularly in tasks involving rate of movement.

It was later demonstrated that language impaired children could be differentiated from normal matched controls 98% of the time through the use of discriminant function analysis based solely on tests of basic rapid perception and production abilities.

Temporal Processing, Speech Perception, and Hemispheric Asymmetry

The research reviewed above strongly supports the hypothesis that some developmental language disorders may result from a primary impairment in auditory temporal analysis. However, one major criticism of the hypothesis that deficits in nonverbal auditory perception are critically involved in some language disabilities has been the contention that nonverbal and verbal auditory processing occur in different hemispheres of the brain. Milner (1967) demonstrated empirically that left temporal lobectomy selectively impairs the learning and retention of verbal material, whereas removal of the right, nondominant temporal lobe leaves verbal memory intact but impairs the recognition and recall of nonverbal auditory patterns. Evidence for this specialization in normal subjects has been demonstrated using the dichotic listening paradigm. When two different acoustic stimuli are presented simultaneously, one to each ear, most right-handed listeners report more accurately verbal stimuli presented to the right ear and nonverbal stimuli presented to the left ear. Based on evidence from electrophysiological studies of the auditory cortex of animals, Kimura (1967) interpreted this asymmetry as evidence that each hemisphere receives input from the contralateral auditory pathway more effectively than from the ipsilateral auditory pathway. Thus, improved recall of information presented to the right ear has come to be indicative of superior left hemisphere processing, while better recall of information presented to the left ear suggests right hemisphere processing. Kimura further substantiated her hypothesis by demonstrating that patients, known by intracarotid sodium amytal tests to have speech represented in the left hemisphere, are more accurate in reporting dichotic speech sounds presented to the right ear. Conversely, patients known to have speech representation in the right hemisphere are more accurate in reporting those speech sounds presented to the left ear.

Additional evidence confirming the superiority of the left hemisphere for processing verbal auditory stimuli and the right for processing nonverbal auditory stimuli has been obtained from studies employing evoked potential procedures. These studies demonstrated that, when human listeners hear speech sounds, greater electrical potentials are recorded by electrodes placed over the left hemisphere than over the right hemisphere. In contrast, when listeners hear nonverbal acoustic stimuli, such as musical segments, there is no difference in electrical activity noted by the same electrode array (Wood, Goff, & Day, 1971).

Although these studies, using a variety of techniques and subject populations, consistently demonstrated a dissociation between the processing of nonverbal and verbal auditory stimuli, the mechanisms underlying these processes could not be established from early studies. More recently, however, computerized techniques for synthesizing speech while selectively controlling various acoustic variables have been utilized to investigate how speech is distinguished from nonspeech and how it comes to be processed in the left hemisphere.

Results of initial studies using computerized synthetic speech demonstrated that, when presented dichotically, not all classes of speech sounds produced the expected right ear advantage (REA) indicative of left hemisphere processing. Studdert-Kennedy and Shankweiler (1970) found that, although stop consonant-vowel syllables /ba, da, ga, pa, ta, ka/ produced the expected REA when presented dichotically, isolated vowels presented dichotically did *not* produce an REA. Based on these finding, Cutting (1975) suggested that specific acoustic characteristics of various classes of speech might contribute to which hemisphere processes them most effectively. To investigate this, Cutting studied three classes of speech sounds that differed acoustically and demonstrated that they each showed different degrees of REA's. The largest REA was produced when stop consonants were presented dichotically in pairs; liquids /1, r/ produced a less strong REA, and steady-state vowels did not produce an REA. Cutting concluded that hemispheric specialization for processing auditory information cannot be explained solely in terms of whether stimuli are or are not verbal. Rather, different magnitudes in the REA occur systematically for different phonetic classes.

In addition to phonetic differences, the classes of speech sounds investigated by Cutting also differ in the rate of change of acoustic cues which characterize their spectra. In fact, it is important to note that the stimuli that gave the largest REA in Cutting's studies (ba, da, ga, pa, ta, ka) are the same stimuli that Tallal and her colleagues have found to be most difficult for language impaired children with rate processing deficits to perceive and produce. Thus, it can be hypothesized that a critical factor underlying the REA for speech may relate to acoustic rather than phonetic components. The results of several recent studies with normal subjects lend indirect support to this hypothesis. These studies demonstrate, contrary to expectation, that certain *nonverbal* acoustic processing, requiring rapid and/or sequential analysis, occurs preferentially in the dominant rather nondominant hemisphere. Right ear advantages, which are presumed to reflect left hemisphere processing, have been found using nonverbal stimuli, such as sawtooth waves differing in rise time, rapidly presented tonal sequences, and stimuli differing only in duration (Berlin, 1976; Mills & Rollman, 1979).

Data contrary to the hypothesis that attributes the left cerebral hemisphere with specialization for verbal auditory information and the right hemisphere for nonverbal auditory information have also been provided from studies of patients with unilateral brain lesions. As early as 1963, Efron found that adult aphasics with left temporal lobe lesions were impaired on a nonverbal auditory perceptual task in which they were required to indicate which of two rapidly presented tones occurred first. Efron's study suggests that the left, rather than the right, temporal lobe plays a primary role in nonverbal acoustic analysis when temporal integration is required. Efron hypothesized that this nonverbal temporal processing deficit may be intimately involved in the language deficit seen in aphasia.

Following Efron's lead with adult aphasics and Tallal & Piercy's with developmental aphasics, Tallal & Newcombe (1978) studied the ability of men with chronic focal brain lesions to discriminate complex tones, synthesized steady-state vowels, and consonant-vowel syllables incorporating rapidly changing temporal cues. The results of this study demonstrated that damage to the left, but not the right, cerebral hemisphere selectively disrupts the processing of rapidly presented nonverbal temporal sequences. Similarly, the results of the speech discrimination studies demonstrated that left hemisphere damage selectively impairs the discrimination of only those speech sounds incorporating rapid temporal changes. Neither patients with right or left hemisphere damage had difficulty discriminating between tone sequences presented more slowly or verbal stimuli incorporating slowly changing or steady-state acoustic spectra. Additional studies with these patients indicated that there was a significant correlation between the number of errors made responding to rapidly presented nonverbal auditory stimuli and the degree of language comprehension impairment. Tallal and Newcombe concluded that damage to the left hemisphere selectively impairs the ability to process rapidly changing acoustic information, regardless of whether it is verbal or nonverbal. The results of these and other studies with adult aphasics suggest that impairment in responding to rapidly changing nonverbal acoustic information, in most cases, is concomitant with language impairment, both being most likely to result from selective left hemisphere lesions.

In light of these psychoacoustic and speech processing studies with both normal and aphasic subjects, the original hypothesis concerning hemispheric specialization for auditory verbal/nonverbal processing may require revision. These data suggest that the superiority of the left hemisphere for processing verbal information may reflect a more primary specialization for processing rapidly changing temporal clues, of which speech is one good example.

In order to test this hyposthesis directly, Schwartz and Tallal (1980) investigated the ability of normal adult listeners to process dichotically presented, phonemically similar, speech sounds incorporating various rates of change in their acoustic spectra. In one condition they used stop consonant-vowel syllables, synthesized with their normally occuring rapidly changing acoustic spectra. In a second condition, they presented subjects with the same speech sounds, but with the rate of change of the critical acoustic cues synthetically extended. Thus, these stimuli were similar along phonemic or verbal dimensions, but differed along auditory temporal dimensions. Recall that these same stimuli were used by Tallal and Piercy (1974) to demonstrate the importance of acoustic rate of change in the speech perception abilities of developmental aphasics. It was hypothesized that, if the REA for verbal stimuli were in fact related to temporal rather than verbal cues, then altering the temporal component of the acoustic spectra within these speech sounds should result in a significant change in the magnitude of the REA for normal adult subjects. The results of the study supported this hypothesis. There was no significant difference observed in the overall accuracy in reporting the syllables synthesized with the various duration temporal cues. This indicated that the syllables comprising each set were equally well recognized as the intended speech sounds. However, there was a significant effect ($p<.01$) as a result of changing the auditory temporal cues within these speech sounds. The magnitude of the REA was significantly reduced when the duration of the temporal cues, critical for discrimination of these speech sounds, was extended.

The findings of Schwartz and Tallal in conjunction with previous reports using other verbal and nonverbal stimuli, suggest that the REA (which is taken to reflect left hemisphere superiority) is significantly enhanced for signals incorporating rapidly changing acoustic spectra, of which speech is only one example.

These data demonstrate that it may be the rate of change of acoustic cues rather than the linguistic nature of the stimuli, per se, underlying left hemisphere processing of verbal stimuli, at least in the initial states of information processing. This is not to suggest that the left hemisphere is not specialized for processing linguistic material at higher levels of analysis. In conclusion, important changes are occurring in theories pertaining to hemispheric specialization, specifically as they relate to auditory temporal perception and speech perception. These advances bring more closely into focus the impact of the neuropsychological research with language impaired children. The data pertaining to the temporal processing deficits of these children stimulated further research into the relationship between temporal processing and hemispheric specialization for speech perception in normals. The results of these later studies lend strong support to our original hypothesis that basic temporal processing deficits could play a critical role in the speech and language disorders of children with developmental aphasia.

Looking ahead to future research in this area, advances may be expected from research comparing the growing body of data on auditory temporal perception with that on the production of temporal events, especially as they both relate to speech. For example, Mateer and Kimura (1977) reported that damage to the dominant hemisphere, resulting in aphasia, also disrupts the ability to *produce* nonverbal motor sequences. Stark and Tallal (1979) have also demonstrated that children with developmental dysphasia show a strikingly similar pattern of errors both perceiving and producing specific temporal cues within speech. Ojemann and Mateer (1979) have recently provided data obtained from stimulation mapping studies performed during craniotomies that suggest a possible biological basis for linking temporal perception and production. They demonstrated that nonverbal sequential orofacial movements and phonemic discrimination of stop consonant-vowel syllables, incorporating rapidly changing acoustic spectra, are both altered by stimulation to the same brain sites. These findings, converging from studies employing a variety of techniques and subject populations, provide a possible biological basis for similar perception/production mechanisms in the dominant hemisphere which underlie the language system. Failure to develop, or delay in the development of, these mechanisms may be implicated in specific developmental language disorders.

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