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In the final paragraph of her recent book *Uncommon Understanding*, Bishop (1997), concludes her comprehensive review of the research literature on etiology, assessment and treatment of children with receptive language impairments with the following quote:

“The ultimate test of a hypothesis is through experimental manipulation. If one believes one has identified the primary process that is implicated in SLI, then by ameliorating that deficit, one should be able to show beneficial effects on other aspects of language development. Although applications to intervention are frequently cited by researchers as justification for doing experimental studies, all too often the link with clinical practice is never made. It is time for researchers to recognize that intervention studies are not just an optional, applied adjunct to experimental work, but that they provide the best method available for evaluating hypotheses and unconfounding correlated factors. Intervention studies, such as the methods for sharpening discrimination of rapid auditory stimuli, experimental vocabulary training work, and morphological learning studies, are still very new, but they generate excitement precisely
because they allow us to test causal theories directly, and to monitor the
process of comprehension development as it occurs”.

Bishop points out here that not only is it an important aim of research on
developmental language disabilities to have this research lead to better assessment and
remediation services for affected children, but conversely, remediation research may be
one of the strongest means of testing competing research hypotheses. One example
mentioned by Bishop, of intervention research that is generating excitement, is the use of
acoustically modified speech, coupled with adapted neuroplasticity training, to ameliorate
language-based learning disabilities. This research was first published in two papers in
*Science* (Tallal et al, 1996; Merzenich et al, 1996) with additional field trial studies
published in a series of subsequent papers (Tallal, 1998; Tallal et al, 1998; Miller et al,
1999; Merzenich et al, 1999; Tallal et al, In Press; Merzenich et al, In Press). These
remediation studies grew out of over 25 years of basic and clinical research in two
distinct disciplines. One utilized primarily behavioral methods to study the etiology of
developmental language-based learning disabilities. The other utilized primarily
physiological methods to study neuroplasticity, that is, physiological changes in the brain
driven by behavioral training techniques. These remediation studies, conducted both in
the laboratory as well as in clinics and classrooms across the USA and Canada have led
to the development of a new generation of training programs, the first of which is called
Fast ForWord®. The focus of this paper will be to review the scientific studies that led to
the development of these new remediation techniques, based on neuroplasticity research, as well as the outcome data derived from controlled laboratory studies and field trials aimed at assessing the efficacy of these new training methods.

Early studies focusing on the etiology of developmental language impairments date back to the early 1960s. In a classic paper, Benton (1964) hypothesized that central auditory processing deficits may characterize many children with developmental dysphasia, now referred to as specific language impairment (SLI). Subsequent studies focused on one aspect of central auditory processing, that is, sequencing or temporal order judgement (TOJ) deficits.

Pursuing these early studies, Tallal and Piercy (1973 a; 1973 b) set out to investigate further the auditory perceptual abilities of children with developmental dysphasia. In addition to an experimental temporal order judgement (TOJ) task, they included a frequency discrimination task as a control condition. In both the TOJ and the frequency discrimination task the identical set of stimuli were presented. Stimuli consisted of two 75 msec duration complex tones that differed in fundamental frequency (100Hz vs 305Hz). All possible combinations of these two stimuli were presented in pairs. The two tones in the pair were separated by a silent interval of varying duration (inter-stimulus interval – ISI). In the TOJ task the child was trained to press two response buttons, to indicate the temporal order of the two tones. If the same tone was presented twice, the button representing that tone was pressed twice. If two different
tones were presented, the child was trained to indicate which one came first and which second, using the two-button response panel. In the discrimination task, children were trained on the same two-button response panel to push one button if the two tones in the pair were the same and the other button if they were not the same. Thus, the stimulus set and the response panel were the same across tasks, but only one of the tasks required temporal order judgements. Twelve children with developmental dysphasia, (aged 6-9 years) and twelve age- and performance IQ-matched controls participated.

Based on earlier studies it was expected that children with language impairments would perform poorly only on the TOJ task. Surprisingly, this is not what the results showed. Contrary to expectation, these children had no difficulty either on the TOJ or the discrimination task, when the brief (75 msec duration) stimuli were presented relatively slowly (separated by hundreds of milliseconds ISIs). Furthermore, they were impaired on both tasks in comparison to matched controls, when these brief stimuli were presented rapidly in succession (tens of milliseconds ISIs).

These results changed the interpretation of the auditory processing problems of children with developmental dysphasia from a focus on sequencing (TOJ) deficits per se, to a more basic rate processing constraint affecting multiple levels of acoustic analysis (attention, discrimination, sequencing, serial memory).

The finding that children with developmental language learning problems are impaired in their ability to process brief, rapidly successive acoustic stimuli, specifically
in the tens of millisecond time window (often referred to as a “temporal processing”
deficit, although it is important to keep in mind that the deficit encompasses frequency
changes that occur rapidly in time as well), has had significant impact on research on the
neurobiological basis of speech perception. These acoustic studies with nonverbal
stimuli focused attention on the acoustics of speech, specifically on how the brain
processes the brief, rapidly successive acoustic changes (spectral, amplitude and
durational) that characterize speech.

We know that the most basic unit of any language is the phoneme, the smallest
unit of sound that differentiates meaning. However, we know very little about how the
individual phonemes of a language come to be represented neurobiologically in the brain.
As phonemes are physically complex acoustic stimuli, the role that complex auditory
processing plays in the development of phonological systems has been a topic of
increased research concentration.

It has been increasingly documented that phonological systems are developed
through exposure to the native language (Kuhl et al, 1997). As the infant is exposed to a
continuous speech stream from the environment, she must parse the incoming acoustic
signal into consistent, replicable chunks that will come to represent the phonemes of her
language(s). Clearly the infant does not know which language or languages she will be
exposed to. Rather, neural firing patterns that recur most frequently in response to the
incoming speech stream will come to be represented as the building blocks, phonemes, of the native language.

Neurophysiologists have mapped the features of the sensory world at the single cell level. This is done by inserting an electrode into a single neuron in the brain and observing which features of a stimulus makes the cell fire. This work has shown that within each sensory modality the features that represent the physical world come to be mapped neuronally in a highly organized fashion. For example, in the auditory modality, there is a tonotopic representation of frequency such that the single cells that fire to a specific frequency, reside physically right next to the cells that fire to the next higher frequency, in a continuous manner throughout the frequency range (Clopton et al, 1974). That these sensory maps must be learned from environmental exposure is evidenced by neurophysiological research showing the effects of sensory deprivation (Neville, 1985).

Although it was previously thought that environmental exposure had to occur during critical periods of development, and, once established, these maps were immutable, more recent research has challenged that perspective. For example, Jenkins, Merzenich, and colleagues have recently conducted a series of elegant studies in adult monkeys that have shown that the neural representations for the fingers on the hand can be significantly altered through training (Jenkins et al, 1990). (Figure 1 here) Figure 1 shows the results of a prototypical training study. This study begins by mapping the somatosensory region that represents the primate hand, neuron by neuron. Here we see
that the fingers of the hand are represented topographically at the neuronal level in a manner similar to the spatial representation of the fingers on the hand on the animal’s body. In this figure, the thumb is labeled as digit 1 and the little finger as digit 5. The top half of the figure shows the neurons that fire when each of the fingers is individually stimulated. The neurons that fire for stimulation to touches on fingers 2 and 3 are shaded. The bottom half of the figure shows the change in neuronal representation that occurs after the animal has engaged in intensive training that requires it to focus its attention on stimulation presented in rapid succession to digits 2 and 3. As can be seen, after training the number of cells that respond to stimulation on digits 2 and 3 have significantly increased. These changes in the sensory map are the physical instantiation of sensory learning in the brain.

What aspects of learning are necessary to drive these physiological changes? Behavioral training studies coupled with physiological recording at the level of the single neuron have shown that there are several components of the learning process that are critical. First, the subject must attend closely to features of a sensory task. Second, in order for attention to be maintained, the subject must be able to perform the task at a high level of accuracy. If the task is too difficult, learning cannot be achieved and changes in the sensory map do not occur. Behavior must be reinforced in a highly consistent and rewarding manner to maintain motivation and drive learning through corrective feedback. Highly consistent, repetitive input must be given over an intense period of time so that
consistent patterns of neuronal activation occur repetitively, sharpening specific stimulation patterns to “represent” this input from the environment in the brain. Finally, having established a behavior that can be responded to accurately and consistently, learning can be driven most effectively by systematically increasing the difficulty of the task as the subject’s performance improves. Merzenich and colleagues have referred to these features of the learning process as “scientific learning principles” and have demonstrated that neuroplasticity at the neuronal level accompanies behavioral learning (Merzenich & Jenkins, 1998).

What can our understanding of learning in the somatosensory system in the hand of the monkey teach us about the development of speech perception? After all, the physical relationship of the fingers of the hand occur in an invariant way on the body of the animal, which is certainly not the case for the phonemes that are the building blocks of languages. How do we know that the animal is not born with distinct neuronal connections already in place to represent each part of the body? A second experiment by Wang et al. 1995, addresses this important issue. In this experiment, illustrated in Figure 2, the monkey is trained in a different task. (Figure 2 here) Instead of receiving individual touches in rapid succession to fingers 2 and 3, as was the case in the first experiment, in this experiment the monkey receives simultaneous stimulation across all four fingers (excluding the thumb), either to the tips of the fingers or to the base, near the palm. Imagine a pencil striking the tips of all four fingers simultaneously, followed by
the base, then the tips, then the base. However, on occasion, instead of alternating the location of stimulation, the pencil strikes the same location twice in a row – either the base and the base again, or the tips and the tips again. The task is to detect this change.

When the “scientific learning principles” were applied to this training procedure in awake behaving adult monkeys, something quite remarkable occurred in the monkey’s brain. As can be seen in Figure 2, instead of the individual fingers being represented as five distinct entities, after training all four fingers were represented as a single entity in two groupings, tips and base, separated by inhibitory neurons between these two groupings.

Importantly, this experiment demonstrates the fundamental role of learning in building neural representation from sensory input. Even for body parts, complex neural representations are learned through experience, and can be altered throughout the lifetime with training. This experiment also demonstrates another basic organizing principle underlying the development and maintenance of neural representations, that is, the profound impact of input timing of neural stimulation on the development and maintenance of sensory maps. When sensory inputs enter the nervous system differentially in time, as is the case when the five fingers of the hand move separately one from the other, and hence receive information differentially in time, the neuronal representation for each finger develops as distinct and separable. However, when information enters the nervous system either simultaneously, or within a critical window of time (tens of milliseconds) that is too rapid to separate, the information is “bound”
together and thus is neurally coded as a unit. It has been hypothesized that it is in this way that the many different physical features of a complex stimulus, such as speech, are combined (bind together) to form a unified percept (Llinas et al, 1998; Ribary et al, 1998).

As speech is at its essence a complex sensory signal, these neurophysiological sensory mapping studies tell us a great deal about how the brain may come to represent it. Think about the processes that occur in the brain of the infant as she experiences the ongoing acoustic waveform of speech. It is widely held that language is an innate capacity that develops automatically, without the need for explicit training. However, recent cross-linguistic research shows that this is not the case (Kuhl et al, 1997), at least for phonology. As each language has its own set of phonemes, and as the infant has no way of knowing which native language he will be born into, the phonemes of the native language must indeed be explicitly learned from environmental exposure to the native language and represented as distinct firing patterns in the auditory cortex. It is important to note here that explicit training does not refer to conscious teaching, but rather explicit, repetitive environmental exposure.

But how does this representation occur? As is the case in all other sensory modalities, the complex acoustic information within the waveform of speech is broken down into its distinct physical features, each of which is represented in fine grained detail in the auditory system (Kraus et al, 1995). The neural mechanisms underlying the
development of representations for complex sensory or motor patterns were elegantly
described by Hebb. According to Hebb (1949), when a complex signal occurs, all of the
neurons that are activated by this complex series of features, per unit time, fire
simultaneously. Repeated exposure to consistent sensory input features will result in that
input pattern being neurally represented as a unified percept. The likelihood that a
particular pattern will come to be represented increases with each additional exposure of
a firing pattern ensemble.

It would be a simple matter to understand how the individual phonemes come to
be represented in this way if they occurred one at a time, in an invariant acoustic pattern,
with distinct boundaries separating the end of one from the beginning of another.
However, none of this is the case. Rather, speech occurs in an ongoing acoustic stream
(waveform) without distinct boundaries. The acoustic patterns produced by the
articulators differ from utterance to utterance, especially within different phoneme
contexts (Liberman et al, 1967), with the acoustic features of one phoneme effecting and
coa-occurring with those of adjacent ones. This is called coarticulation. For example, the
acoustic pattern produced by the phoneme /b/, differs markedly depending on the
differing vowel context in which it can occur. Further, in ongoing speech there is no
distinct boundary that tells the brain where one phoneme ends and the next one begins.
In learning to represent the acoustic world of speech the brain must segment the ongoing
speech stream into chunks of time, and then seek consistencies in the neural firing
patterns that result from these segmented chunks. Consistencies can be derived from chunking across various units of time. Smaller chunking units (in the tens of millisecond time window) will result in representations consistent with individual phonemes within a language. Chunking across a larger time window (hundreds of milliseconds) will equally result in consistent firing patterns, but in this case the firing patterns will be consistent with syllable level representations rather than phoneme representations.

The experiments described above showed that whether the fingers of the hand are represented in the brain as distinct, individual units, or more broadly (like a paw), is based primarily on the timing inputs of sensory stimulation. Similarly, speech may be represented in fine grain phonetic precision or more course grained syllabic precision, depending on temporal parameters of segmentation applied to the ongoing speech stream.

**Specific Language Impairments**

Now, let us return our focus to studies of individuals with phonological processing problems that affect either oral and/or written language learning. Over the past 30 years, substantial evidence has been reported in the scientific literature that demonstrates that many individuals with language learning impairments integrate information across a longer (hundreds of milliseconds) time window, where as those with typical language and reading abilities are capable of integrating within a more fine grained (tens of millisecond) time window. This rate processing constraint occurs across sensory modalities (auditory, visual, somatosensory). Table 1 lists some of the many
studies demonstrating this finding, when non-verbal stimuli are used. Farmer & Klein, 1995 and Leonard, 1998 provide excellent reviews of this literature.

But how does this processing rate constraint specifically impact speech perception? (Figure 3 here) Figure 3 shows two sets of speech syllables. The first set are examples of vowels that incorporate acoustic spectra that differed one from the other across hundreds of milliseconds, such as the vowels ( /a/ ) as in the word “body” vs /ae/ as in the word “bat”. The second set are the two stop-consonant vowel syllables /ba/ as in the word “body” vs /da/ as in the word “dot”. These syllables begin with a brief segment, comprised of a 40 msec duration formant transition followed rapidly in succession by the steady-state vowel formants. Discrimination between these syllables depends on the ability to process the brief duration formant transitions (which incorporate coarticulated information about both the consonant and following vowel) within the context of the rapidly successive vowel formants. Numerous studies across many laboratories have demonstrated that children with language learning impairments are often most impaired in discriminating speech syllables that incorporate brief, rapidly successive acoustic changes intra-syllabically (see Table 2). It is important to emphasize that these studies show deficits that occur in processing rapid acoustic changes that occur intra- syllabically (within the syllable), not inter- syllabically (between syllables or words). Several recent studies, notably Mody, Studdert-Kennedy and Brady (1996) have misinterpreted these findings and have manipulated intervals between syllables, rather
than rates of change within syllables, focusing on TOJ rather than discrimination. Not
surprisingly, they fail to replicate the results found repeatedly in the many studies listed
in Table 2.

That discrimination deficits for phonological contrasts that incorporate brief,
rapidly successive acoustic changes are specifically related to the duration of intra-
syllabic acoustic cues was demonstrated initially by Tallal and Piercy (1975). In this
experiment the duration of the formant transition within the syllables /ba/ and /da/ was
extended from 40 to 80 msec, while the duration of the following steady-state portion
representing the vowel was reduced from 210 to 170 msec. This acoustic modification
resulted in highly significant improvement in discrimination. The significant benefit of
acoustically extending the brief intra-syllabic cues within the speech waveform has been
replicated across several studies (Frumkin & Rapin, 1980; Alexander & Frost, 1982).

The studies listed in Tables 1 and 2 demonstrate a concurrent relationship in
young school age children between language disorders and rate processing constraints.
But, they do not allow us to look at developmental interactions, prospectively. However,
a recent series of studies has demonstrated that acoustic segmentation rates in infancy
may play a fundamental role in the rate of normal as well as abnormal language
development (Benasich & Tallal, 1996; Benasich & Tallal, 1998). In these studies the
auditory temporal integration threshold of infants born into families with a history of
language learning problems was assessed at six months and compared to that of infants
born into families with no history of language or learning problems. Figure 4 shows an example of the significant difference in the auditory temporal processing threshold obtained in a representative family history positive as compared to a family history negative child. (Figure 4 here)

The familial nature of language learning problems has been established in a number of studies (Tallal et al, 1989 a, 1989b; Gilger et al, 1994; Tomblin et al, 1992; see Leonard, 1998 for review). An autosomal dominant mode of genetic transmission appears to be most consistent with these data. This entails that, every infant with an affected parent or sibling will have a 50% chance of also having a language learning problem. Spitz et al, 1997, found that at six months of age, approximately half of the infants in a family history positive group had auditory temporal integration thresholds in the hundreds of millisecond time window, (similar to that shown for a representative infant born into a family with a positive history of language impairment in Figure 4), whereas the other half had integration thresholds in the tens of millisecond time window, similar to the threshold shown in Figure 4 for a representative infant with a negative family history. These infants have been followed prospectively by Benasich and colleagues and their language development has been assessed longitudinally using the MacArthur Child Development Inventory (Fenson et al, 1993). Importantly, the auditory temporal integration thresholds established at six months of age, for both groups of infants, have proven to be highly predictive of subsequent receptive and expressive
language development. These data show that those infants with slow temporal integration rates are developing language more slowly than those with more rapid integration rates (Benasich & Tallal, 1996, 1998). A similar finding has been reported by Trehub and Henderson, (1996) using a measure of gap detection threshold in a large cohort of normally developing infants. These findings suggest that individual differences in acoustic information processing rates, present within the first months of life, play a significant role in language learning. Preliminary results suggest that the infants with both the slowest processing rates, and who also have a family history of language learning impairments, are most at risk to become language learning impaired.

**The Language Literacy Continuum**

There has been a good deal of discussion about the possible relationship between oral language and written language deficits. As part of this discussion, it has been hypothesized that children who segment speech in larger time chunks will not only experience difficulties learning phonological skills necessary for oral language development, but also for written language. Specifically, they may be expected to have considerable difficulty being able to learn to segment words into the finer grain phonetic units important for developing phonological awareness skills that are necessary for establishing letter to sound correspondence rules so important for learning to read. To investigate this hypothesis, the processing rate of individuals experiencing written language problems (dyslexics) has been studied extensively and also related to those of
children with oral specific language deficits (SLI) (see Stark & Tallal, 1988 and Farmer & Klein, 1995 for reviews). Results across many studies have shown a highly significant correlation between difficulty with phonological decoding, and a slow rate of information processing. For example, an early study by Tallal (1980) showed a highly significant correlation between the rate of processing brief, rapidly successive tones differing in frequency, and error rates for reading nonsense words in dyslexic children. Importantly, it was shown in this study that not all dyslexic children showed rate processing constraints. What was striking was the relationship between rate processing constraints and reading decoding skills. Those dyslexic children who did not demonstrate rate processing constraints also were not impaired in either reading decoding skills or oral language comprehension abilities. They did have reading problems, but these did not seem to be based on phonological processing or awareness deficits. More recently, Witton et al (1998) have shown a very similar correlation between processing rapidly modulating tones, as well as visual transient stimuli, and nonsense word reading in adults with a history of dyslexia.

Deficits in responding to rapidly successive acoustic stimuli also have been demonstrated physiologically in a recent study using magnetoencephalography (MEG), a neuroimaging technique that records magnetic signals emitted from the surface of the skull with excellent spatial as well as temporal precision (Nagarajan et al 1999). (Figure 5 here) Figure 5 shows the neurophysiological MEG response to two brief acoustic
stimuli presented with differing inter-stimulus intervals (ISIs). The top half of the graph shows the neurophysiological response of normal adults without a history of language or reading problems. Here it is seen that two distinct, positive neural responses (indicated by a sharp positive peak in the recording) occur for each of two distinct, successive acoustic stimuli separated by a 50 msec ISI. The bottom of this graph shows the brain responses to the same stimuli for adults with dyslexia. It is seen clearly that although the neural response to the first stimulus is initiated normally (as indicated by a sharp positive peak in the recording), this response is prolonged over time (as indicated by the period of time taken to return to baseline). For the dyslexic subjects, this prolonged response to the first stimulus continues well into the period in which the second response (seen in the recordings from the control subjects as a second sharp peak) should have, but does not, occur. In this study it was found that the dyslexic subjects required several hundred milliseconds ISI before a second neural response occurred. These neurophysiological data mirrored these subjects’ behavioral perception of whether they heard one or two successive tones. These results demonstrate that when brief, rapidly successive acoustic stimuli converge in the nervous system within tens of milliseconds, these signals are not processed normally in the brains of people with dyslexia.

These results taken in aggregate demonstrate that certain individuals begin life as slow acoustic processors and this information processing rate constraint continues throughout the life span. In addition to slow processing rates, these same individuals are
generally characterized by both oral and written language deficits. After comprehensively reviewing the extensive research literature pertaining to the etiology of specific developmental language impairments (SLI) in children, Leonard, (1998) finds that “The conclusion that children with SLI have difficulty processing brief or rapidly presented stimuli seems indisputable. These findings are so consistent and demonstrable across tasks and stimulus variations that it is difficult to imagine that they are not an important piece of the SLI puzzle.”

Given the consistency of these findings across so many studies and laboratories, it is important to try to determine why a few recent studies have reported difficulty replicating these results (Mody et al, 1996; Nitterouer, S., 1999). These discrepancies can likely be related to differences in subject selection criteria and important stimulus design and other methodological differences between studies. Understanding these differences, rather than simply viewing them as a failure to confirm past research, will help to extend and refine our understanding of the perceptual constraints of individuals with language learning impairment and how they relate to the language and reading problems of these individuals.

Whereas the direct effect that acoustic rate processing constraints may play on the development of fine grain phonological representations has been extensively studied, the extent to which a general rate processing constraint can affect higher level aspects of linguistic development has received far less experimental attention. Leonard (1998) (also
see Leonard this volume) addressed this issue in considerable detail. Leonard comprehensively reviewed cross-linguistic studies that focus on the linguistic error patterns of children with specific language impairment (SLI) learning a variety of different languages. It was expected that cross-linguistic data would replicate the pattern of linguistic deficits that have been reported so consistently for English speaking children with SLI (see Rice & Wexler, 1996 for review, and also Rice this volume). Leonard hypothesized that if children with SLI have a linguistic specific deficit, as has been proposed as the basis of SLI, then a consistent pattern of linguistic deficits should be seen, regardless of the language that a child is learning. Despite the broadly held view that SLI represents primary and specific linguistic deficits, extensive cross-linguistic studies have failed, on the whole to support this hypothesis. That is, few specific linguistic patterns of errors have been found that are consistent across all languages. For example, Rice & Wexler (1996) have suggested that children with SLI have a specific deficit in grammatical morphology, particularly past tense verbs. However, children with SLI learning more highly inflected languages such as Italian, fail to show a similar pattern of errors. After reviewing an extensive literature focusing on the linguistic patterns of errors of children with SLI learning dozens of different languages, Leonard concluded that there is little support for a linguistic specific deficit in these children. Rather, children across all of these languages show a protracted rate of language
Leonard goes on to make a strong case for a different interpretation of linguistic data obtained cross-linguistically from children with SLI. He discusses two plausible and compatible hypotheses. One of these – the morphological richness hypothesis -- pertains to the frequency and obligatory nature of inflections in the target language. The other is the surface hypothesis. According to this hypothesis, whichever linguistic structures in a particular language are acoustically brief and of weak phonetic substance are most difficult for all children to learn, and are particularly problematic for individuals with SLI. Fellbaum et al (1995) designed a study in English speaking children to address this hypothesis directly. (Figure 6 here) Specific English morphologic structures were selected that are brief and have weak phonetic substance (including plural – s; regular past tense – ed; nominative case pronouns – he, she, they; modal auxiliary – will; possessive – s). These were compared to linguistic structures, typically learned by children across the same age range, that in the most frequent obligatory contexts are acoustically longer, stronger and hence have more phonetic salience (including: object pronouns – him, her; comparative – more, comparative – er). The results of this study were striking. In comparison to children with typical language development, English speaking children with SLI make significantly more errors on the brief, phonetically non-
salient morphological structures as compared to the longer morphological structures. These results support the surface hypothesis.

Leonard concluded his recent, comprehensive review of the literature on SLI by proposing an integrating theory that best seems to account for the acoustic, perceptual, conceptual, neuroscientific and linguistic data in this field. According to this review, much of the data, regardless of scientific approach used, fit parsimoniously with a general information processing constraint that specifically affects the rate of information processing across sensory modalities, and affects both verbal and non-verbal information processing.

**Remediation Studies**

If language learning problems are characterized by a basic processing constraint in the rate at which incoming sensory information is segmented and represented, (Tallal’s rate processing hypothesis and Leonard’s 2\textsuperscript{nd} hypothesis), and also is affected by the frequency and obligatory nature of morphological structures in a target language (Leonard’s 1\textsuperscript{st} hypothesis) these factors should have important implications for the design of remediation strategies. Recently, Tallal, Merzenich, Miller and Jenkins (1998) hypothesized that the “scientific learning principles”, that had been shown in studies with monkeys to drive neuroplasticity, might be adapted to ameliorate the rate processing constraints of children with language learning problems, while simultaneously using neuroplasticity training procedures to train linguistic skills based on frequency of
obligatory occurrence. Specifically, a hierarchy of computer-based training exercises now called Fast ForWord® was developed to 1) attempt to drive neural processing of rapidly successive acoustic stimuli to faster and faster rates and 2) to improve speech perception, phonological analysis and awareness and language comprehension by providing intensive training exercises within various linguistic contexts (phonological, morphological, semantic and syntactic) that utilize speech stimuli that have been acoustically modified to amplify and temporally extend the brief, rapidly successive (phonetically non-salient) intrasyllabic cues (see Nagarajan et al, 1998 for a detailed description of the speech modification algorithm). Seven training exercises were developed in the form of computer games. The exercises were programmed to be individually adaptive. That is, the goal was to find for each child a level of acoustic and linguistic functioning that could be responded to at a high rate of accuracy, through the use of acoustically modified speech. Once established, the exercises were programmed to adaptively change trial by trial, based on each individual child’s responses. That is, trials got more difficult (moving towards more rapid and less amplified, natural speech) following correct linguistic responses or more simplified (more acoustically modified) following incorrect responses. The goal was to move the individual child from a reliance on the acoustically modified speech towards the ability to process more and more complex linguistic tasks with rapidly successive, natural speech. Similarly, adaptive training was also undertaken to directly effect temporal integration thresholds for rapidly
successive acoustic sweep tones. The goal was to drive, through adaptive training, each child into the normal processing rate of tens of milliseconds, while simultaneously increasing each child’s ability to process linguistic structures in their most frequent, naturally occurring, obligatory contexts.

Two initial laboratory studies demonstrated dramatic success with a prototype of this training method (Merzenich et al, 1996; Tallal et al, 1996). (Figure 7 here) The results seen in Figure 7 showed that intensive daily training (approximately two hours a day five days a week for four weeks) resulted in highly significant improvements in temporal integration rates, speech discrimination, language processing and grammatical understanding. This controlled laboratory study demonstrated the specificity of this training method. A control group received essentially identical language training, but using natural, unmodified speech. In addition, they played computer games for an equivalent period of time. However, these computer games were visual, not auditory, and were not temporally adaptive. Both groups received the same amount of training, reinforcement and rewards for performance. The results showed that the control group demonstrated significantly poorer outcomes than the group that received the acoustically modified speech and rate processing training.

Moving Research from the Laboratory to Clinics and Classrooms

Based on these initial promising results from controlled laboratory studies, two large-scale field trials have been conducted to assess the efficacy of the Fast ForWord
training program in clinical and educational settings. The purpose of the first trial was to
determine whether the efficacy that was demonstrated in the laboratory could be
replicated in clinics and classrooms under the supervision of clinicians and teachers
(rather than trained researchers). This is a difficult, but an essential first step in the
process of moving research from the laboratory into clinics and classrooms. In order to
assure consistency in program delivery, data collection and analysis, and quality control
across multiple sites and long distances, the adaptive training programs were created in
the form of a CD-Rom which could be activated and monitored through data exchange
over the Internet. Trial by trial responses for each of the seven exercises in the program
are recorded on the hard drive of the computer each child uses to play the games. These
responses are sent daily, coded by individual client ID numbers, over the Internet to
Scientific Learning Corporation (the company that produces the programs) where they
are analyzed, tabulated, and then returned to the professional supervising the training for
each child (for more details see www.scientificlearning.com).

The first field trial included over 500 children identified by 60 professionals at 35
clinical or educational sites. Clinicians were instructed to use standardized speech and
language assessment tests to include children who were at least one or more standard
deviations below the mean in the area of central auditory processing, speech
discrimination and/or language comprehension. Clinicians were encouraged to select a
battery of standardized speech, language and central auditory processing tests that they
used most commonly in their own clinical practice. Case history records indicated that children who met these study criteria had one or more of the following diagnostic classifications: specific language impairment (SLI), attention deficit disorder (ADD), pervasive developmental disability (PDD), autism, central auditory processing disorder (CAPD), dyslexia or learning disability (LD).

The goals of the first clinical trial were to determine 1) whether or not the results obtained in the laboratory could be replicated, by the clinicians/educators who most often treat children with language/learning problems, 2) whether the result obtained in the laboratory with children with SLI, would generalize to a broader population of children with a variety of speech, oral and written language and central auditory processing disorders, and 3) whether efficacy would generalize to the wide variety of standardized receptive and expressive speech, language and central auditory processing tests that are most commonly used clinically, or just to items similar to those that were directly trained in Fast ForWord.

Results of this field trial represented the first phase of moving this research program from the laboratory into practical use. As such, it was not a controlled trial. This is important because if the results failed to replicate those found in the controlled laboratory study, it would not be possible to determine whether improved performance resulted from practice or placebo effects, rather than the specific aspects of the training program. However, if the results did replicate those found in the controlled laboratory
study, we could rule out these factors as explanatory, as they had already been controlled for in the laboratory studies. As the cost of running such a large scale trial in the field with controls was prohibitive, it was determined that the first step should be an attempt to replicate and extend the results of the previous controlled laboratory studies in “real-world” clinical and classroom settings, using a standardized program presented via CD-Rom, with monitoring over the Internet. A detailed report of the design and results of this first field study are reported elsewhere (Merzenich et al, In Press).

A summary of results are shown in Figures 8, 9 and 10 comparing pre-Fast ForWord training standardized test scores to post-test standard scores for each child. (Figure 8 and 9 here) Figure 8 and 9 demonstrate that the laboratory results were replicated in clinics and classrooms, and thus can be considered a replication of the controlled laboratory studies. Significant efficacy was obtained in areas of central auditory processing, speech discrimination and language comprehension, the areas targeted by Fast ForWord training. However, in addition, results showed that efficacy extended to include improved expressive language abilities as well, although only receptive language skills were directly trained using the Fast ForWord method. Overall, the results of this field trial demonstrated that approximately 90% of children who complied with the study protocol showed increased performance (at least one standardized deviation change from pre-training to post-training) on standardized speech,
language and/or auditory processing measures, regardless of the precise clinical measures selected by each professional.

There was considerable variability across children as to the degree and pattern of improvements they made across domains, as would be expected, based on the variety of symptomatology and clinical classifications of this large heterogeneous group of children with language learning problems. Figure 10 shows that significant efficacy was obtained for a much broader group of children than had been included in the initial laboratory studies. (Figure 10 here) Furthermore, the significant difference in the degree of efficacy was not found to be based on the child’s clinical diagnostic classification or classifications, age, gender or degree of impairment. On average, the language skills of children who completed the protocol improved by a year and a half following six weeks of training. These results are significant not only in magnitude of improvement, but specifically in light of the very brief period of time (weeks rather than years) over which the intervention (training) was provided.

Clearly both the controlled laboratory and clinical field trial results indicate the immediate efficacy of this new training approach. However, it is also very important to determine the longer term effectiveness of this brief, but intensive, training. Figure 11 shows follow-up results for the SLI subjects who participated in the original controlled laboratory study (Bedi et al, 1999). (Figure 11 here) This graph shows that training results were sustained at follow-up at both 3 and 6 months, without additional training.
Children who received the experimental training in the controlled laboratory studies not only maintained their advances as compared to their matched controls, but continued to improve at an accelerated pace compared to the control group during the three months following the conclusion of the program. These significant improvements and group difference were maintained out to six months. Longer term follow-up is currently in progress.

In a second field trial the potential use of these neuroplasticity based training programs for preventing language based learning problems was investigated (Miller et al, 1998). Regular classroom elementary teachers at 19 different public schools in the United States were instructed to select children who they identified as “at risk for academic failure.” The reason for being identified as “at risk” was not specified in this study to relate solely to language based problems.

This second trial represents the second phase of bringing this research out of the laboratory and into the public domain. As such, it was a randomized control trial with children randomly assigned to receive Fast ForWord training, as compared to receiving additional educational services being provided in their public school for “at risk” children, for a comparable period of time (one hour and forty minutes a day five days a week for six weeks). All participants also received a battery of standardized tests both pre- and post- training.
One of the most striking results of this field trial of school children selected as academically “at risk” was the finding that these children’s oral language was their most significant problem, based on pre-training test scores. These results are very interesting in that they show that classroom teachers identified children as academically “at risk”, who upon testing were found to be performing at a lower level on standardized measures of oral language. This is an important finding as these teachers were not instructed or encouraged to select children based on oral language impairment, but rather based on their intuition that a child was “at risk” for academic failure. Nonetheless, on testing, these children as a group showed oral language performance skewed towards the lower range of normal.

This result is consistent with a striking finding from a recently published epidemiological study on the incidence of SLI. Tomblin (1997) reports that on testing 7.4 percent of kindergarten children were found to be more than one and a quarter standard deviations below the mean in oral language skills. Perhaps the most striking finding, however, was that only 29% of the parents or teachers of these children had ever identified oral language problems in these children with SLI. This finding suggests that 71% of oral language deficits may remain undetected and untreated at the time a child enters school. Our school study shows that although teachers are quite accurate in identifying children who are “at risk for academic failure”, they do not select “language comprehension deficit” on a check list when indicating why they think the child is “at risk for academic
failure”. This suggests that they are not aware that it may be weak receptive language skills that they are actually recognizing in these children. As a result, a minority of children with weak language development are ever identified or given speech therapy or other oral language interventions. Thus, the majority of these children with weak oral language skills enter our school systems unidentified and, indeed, at risk for academic failure, which may likely first appear as a problem learning to read, write and spell.

The results of this field study showed that before training, over half of the subjects identified by their teachers as “academically at risk” scored one or more standard deviations below the mean in oral language comprehension. After Fast ForWord training, post-testing results showed that the oral language comprehension performance of these “academically at risk” children substantially and significantly improved, shifting substantially to within the normal distribution. Furthermore, improvements were significantly greater in children receiving Fast ForWord training as compared to the control group (Miller et al, 1998). Children in both groups are now being followed longitudinally in their public schools to determine the longer term efficacy of Fast ForWord as a “prevention” for subsequent reading problems in “academically at risk” children.

**Conclusions**

Our laboratory research over the past 25 years has been based on questions pertaining to the possible etiologies of specific language based learning disabilities. That
research led to the development of a hypothesis that one potential basis for SLI is a pervasive rate processing constraint that particularly effects the development of normal phonological processing and grammatical morphology, leading to both oral and in many cases written language deficits. This hypothesis led us recently to develop a series of laboratory studies that aimed to evaluated the effects of both attempting to ameliorate the underlying rate processing constraints while simultaneously also directly training many aspects of speech and language, using an acoustically modified signal. The results showed that dramatic improvements in temporal integration rates, as well as language processing and comprehension, could be achieved in a short period of time using these new methods.

It is important to note that the specific role of each of the variables manipulated in these initial studies has not as yet been partialled out. As such, we cannot determine which specific variable(s) contribute to the improvements we reported. It is also important to note that the magnitude of the improvements we observed led us away from our previous focus on etiology, to a new focus on the development of practical and efficacious remediation techniques. The nature of the questions posed when developing new remediation techniques are, by their very nature, different from the theoretical concerns that are at the heart of study focused on etiology. It is fair to say that the initial concerns in developing remediation techniques is demonstrating efficacy, not in working out which specific theory best explains the results. As such, the methods of laboratory
research, of carefully changing a single variable at a time and seeing the effect, are not efficient for the initial stages of the development of training programs such as Fast ForWord. To the contrary, the goal is to develop the most effective, generalizable program, by “cross training” as many skills as possible together, in the briefest period of time, to get the greatest improvements across the largest and most heterogeneous population. Once a program is found to be effective, it is a reiterative process to determine what specific training components are most effective, so that the program can be improved. It is at this stage that issues pertaining to theory, that is, what is responsible for the changes in specific targeted areas, can become the focus of research. It is anticipated that many future studies will address these issues.

This report outlines the steps we have taken to date to use data obtained in controlled laboratory studies to develop new diagnostic and treatment approaches for language learning problems, and to move this research from the laboratory to “real world” clinics and classrooms. It is important to emphasize that when we refer to the Fast ForWord training program as “proven”, this is intended to refer to its clinical effectiveness, based on standardized test results and clinical reports, rather than to suggest that it proves any particular theory. It is our primary goal that this line of research will lead to increased progress in improving diagnostic, remediation and educational programs for the millions of individuals affected with developmental
language learning problems worldwide. It is also our hope that future theoretical and etiological research also will be stimulated by these efforts.
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