events and phonetic element contexts and contrasts that occur in natural running speech. The third game (Old McDonald's Flying Farm), produced with Director (Macromedia) software, was a limited hold reaction time task in which the child maintained a touchscreen "button" press while repeated stimuli were delivered in regular sequence. The child's task was to release the button when there was a change in phonetic element identity. The durations of a wider array of synthetic consonant elements and the interstimulus times between repeated stimuli were the main exercise variables. The fourth game (Phonic Match), also developed with Director (Macromedia) software, was a sound-matching exercise in which button presses resulted in soundings that the child had to locate a match for, on a 2-by-2 to 5-by-5 touch-screen button array. The button array size and the temporal structure of elements and of element sequences in individual consonant-vowel-consonant stimuli were game variables. Stimuli applied in this exercise were synthetically processed to prolong and differentially amplify brief phonetic elements [see (*1*)]. Children also played both of these games for approximately 20 min/day throughout the 20-day training period. In general, children's performances at these two games paralleled their progressive achievements at the time order judgment and phonetic element recognition tasks described in this report. All LLI children who were trained at these games also underwent training with acoustically modified speech stimuli, as described by Tallal *et al.* (*7*).

19. Children were still improving at their game performances when these exercises were arbitrarily terminated at the end of the 4-week training period. Their ultimately achievable performance limits are unknown.
20. The Token Test for Children (Teaching Resources Corporation, Boston, MA, copyrighted 1978) is designed to test the ability to follow auditory commands of increasing length and grammatical complexity.
21. The intensity of practice at three FM stimulus categories were all significantly correlated with Token Test (language outcome) results. For the 1+ kHz category, trial numbers versus language outcome, $r = 0.75$, $P \leq 0.01$; for 2+ kHz FM stimulus, trial numbers versus language outcome, $r = 0.73$, $P \leq 0.01$; for 4+ kHz FM stimulus, trial numbers versus language outcome, $r = 0.84$, $P \leq 0.01$. The 0.5+ kHz category practice trial numbers were not significantly correlated with language outcomes ($r = 0.48$).
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Language Comprehension in Language-Learning Impaired Children Improved with Acoustically Modified Speech

Paula Tallal,* Steve L. Miller, Gail Bedi, Gary Byma, Xiaoqin Wang, Srikantan S. Nagarajan, Christoph Schreiner, William M. Jenkins, Michael M. Merzenich

A speech processing algorithm was developed to create more salient versions of the rapidly changing elements in the acoustic waveform of speech that have been shown to be deficiently processed by language-learning impaired (LLI) children. LLI children received extensive daily training, over a 4-week period, with listening exercises in which all speech was translated into this synthetic form. They also received daily training with computer "games" designed to adaptively drive improvements in temporal processing thresholds. Significant improvements in speech discrimination and language comprehension abilities were demonstrated in two independent groups of LLI children.

Exposure to a specific language alters an infant's phonetic perceptions within the first months of life, leading to the setting of prototypic phonetic representations, the building block on which a child's native language develops (*1*). Although this occurs normally without explicit instruction for the majority of children, epidemiological studies estimate that nearly 20% of children fail to develop normal speech and language when exposed to speech in their native environment (*2*). Even after all other primary sensory and cognitive deficits are accounted for, approximately 3 to 6% of children still fail to develop normal speech and language abilities (*3*). Longitudinal studies have demonstrated a striking convergence between preschool language delay and subsequent reading disabilities (such as dyslexia). A broad body of research now suggests that phonological processing deficits may be at the heart of these language-learning impairments (LLIs) (*4*, *5*).

Tallal's earlier research has shown that rather than deriving from a primarily linguistic or cognitive impairment, the phonological and language difficulties of LLI children may result from a more basic deficit in processing rapidly changing sensory inputs (*6*). Specifically, LLI children commonly cannot identify fast elements embedded in ongoing speech that have durations in the range of a few tens of milliseconds, a critical time frame over which many phonetic contrasts are signaled (*7*). For example, LLI children have particular difficulty in discriminating between many speech syllables, such as [ba] and [da], which are characterized by very rapid frequency changes (formant transitions) that occur during the initial few tens of milliseconds. Interestingly, LLI children are able to identify these same syllables when the rates of change of the critical formant transitions are simply synthetically extended in time by about twofold (*8*). A strong prediction is suggested by these findings: If the critical acoustic cues within the context of fluent, ongoing speech could be altered to be emphasized and extended in time, then the phonological discrimination and the on-line language comprehension abilities of LLI children should significantly improve.

To test this prediction, we have conducted two studies with LLI children who have been trained with the application of temporally modified speech. These same children also received training at making distinctions about fast and rapidly sequenced acoustic inputs in exercises mounted in the format of computer "games" (*9*). Modification of fluent speech was achieved by application of a two-stage processing algorithm (*10*). In the first stage, the duration of the speech signal was prolonged by 50% while preserving its spectral content and natural quality. In the second processing stage, fast (3 to 30 Hz) transitional elements of speech were differentially enhanced by as much as 20 dB. This two-step acoustic modification process was applied to speech and language listening exercises that were recorded on audiotapes, as well as to the speech tracks of children's stories recorded on tapes and on educational CD-ROMs. The differential emphasis of fast elements also resulted in a speech envelope that was more sharply segmented. This processed speech had a staccato quality in which the fast (primarily consonant) elements were exaggerated relative to more slowly modulated elements (primarily vowels) in the ongoing speech stream. We reasoned that amplifying the fast elements should render them more salient, and thus

P. Tallal, S. L. Miller, G. Bedi, G. Byma, Center for Molecular and Behavioral Neuroscience, Rutgers University, Newark, NJ 07102, USA.
X. Wang, S. S. Nagarajan, C. Schreiner, W. M. Jenkins, M. M. Merzenich, W. M. Keck Center for Integrative Neurosciences and Coleman Laboratory, University of California, San Francisco, CA 94143–0732, USA.

*To whom correspondence should be addressed.

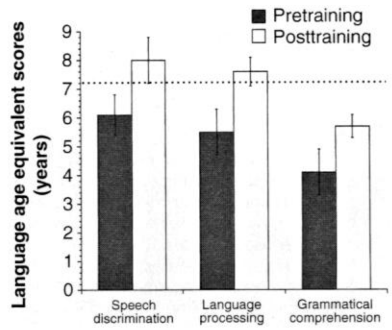
more reliably temporally integrated, and less likely to be subject to forward or backward masking by neighboring, slowly modulated speech elements. That sharpening of the envelope offsets the slower envelope modulation that applies for prolonged speech. Cortical plasticity experiments have indicated that a more sharply modulated form of speech should be more powerful for inducing complex signal learning (*11*).

Seven LLI children participated in a 6-week study aimed at evaluating the effect that exposure to acoustically modified speech had on speech discrimination and on-line language comprehension [see reference 10 of Merzenich *et al.* (9) in this issue for subject characteristics]. In week 1 (pretraining) and week 6 (posttraining), clinical benchmark scores were derived with natural, unprocessed speech by using a series of standardized speech, language, and auditory temporal processing tests (*12*). In weeks 2 through 5 the children rotated each week through a series of 10 different listening exercises that were designed to provide consistent exposure to the acoustically modified speech. Training exercises were conducted for 3 hours a day, 5 days a week, at the laboratory, and 1 to 2 hours a day, 7 days a week as "homework" over a 4-week period. The language exercises (*13*), which consisted of exposure to prerecorded, acoustically modified speech, were delivered one-on-one by trained clinicians as well as through the use of computer games (9) designed specifically for this study. The children also listened to stories on audio tapes or CD-ROMs that had been acoustically modified with the same computer algorithm. The goal was to have the children actively listen to the acoustically modified fluent speech in a highly consistent format, for as many hours per day as possible.

A comparison of pretraining and posttraining test performances is shown in Fig. 1. The LLI children were between 1 and 3 years behind their chronological age in speech and language development based on their pretraining test scores. After 1 month of daily training with acoustically modified speech, a repeated measures analysis of variance showed that posttraining test scores significantly improved [$F(1,6) = 200.1, P < 0.001$] by approximately 2 years, with each of the seven LLI children approaching or exceeding normal limits for their age in speech discrimination and language comprehension.

A second study was done to examine the extent to which the significant improvements in receptive speech and language abilities were replicable in an independent, larger group of LLI subjects, and the extent to which those improvements derive specifically from training with acoustically modified speech coupled with temporal processing training. Twenty-two LLI children participated (mean chronological age = 7.4 years; mean language age = 4.9 years) [see reference 13 of Merzenich *et al.* (9) for subject characteristics]. The design of the first 6-week study was replicated, with some minor revisions, to accommodate the larger number of subjects (*14*). The children were divided into two matched groups on the basis of pretraining measures of nonverbal intelligence and receptive language abilities (*15*). Both groups performed the same training exercises used in study 1. However, to assess the efficacy of the processed speech and temporal training, we presented half of the children (group A) with computer games that adaptively trained temporal processing and with language exercises recorded with acoustically modified speech. The other LLI children (group B) received essentially the same training, but with computer games that were not temporally adaptive, and with precisely the same language exercises, but with natural, unmodified speech.

Fig. 1. Performance of LLI subjects from study 1 on specific speech and language measures was obtained with natural speech before (pretraining) and after (posttraining) 4 weeks of temporal processing training and training with acoustically modified speech exercises. Measures included speech discrimination (GFW test), language processing (Token Test), and grammatical comprehension (CYCLE-R) (*12*). Mean and standard error of the mean data are shown for each measure. Mean chronological age (7.3 years) is displayed as a horizontal dotted bar. Data obtained at posttraining (white bars) reflect significantly higher performance for each measure than the pretraining values (black bars) obtained 4 weeks earlier. Note that performance after training approached or exceeded that expected for normally developing children of the same chronological age.

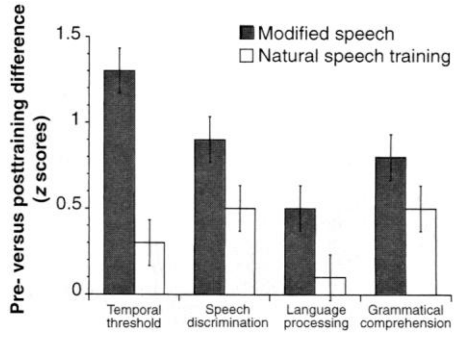


A comparison of the two treatment groups is shown in Fig. 2. A repeated measures analysis of variance comparing performance on pretraining and posttraining measures again showed that performance improved significantly from pretraining to posttraining [$F(1,20) = 34.18, P < 0.001$). Furthermore, improvement made by the children in group A (who received training with temporal modification) was significantly greater [$F(1,20) = 5.44, P = 0.015$, one-tailed] than that of group B.

It should be noted that the LLI children in study 1 and group A in study 2 were trained with exercises designed to improve their reception of rapidly presented and short duration nonverbal and phonetic elements (9) as well as speech and language training with acoustically modified speech. The measured improvement in a child's threshold for correctly segmenting and sequencing successive nonverbal auditory stimuli (*16*) was significantly correlated with posttraining outcome in on-line language processing [study 1, Pearson product-moment correlation coefficient (r) = 0.81, $P < 0.05$; study 2 group A, $r = 0.89$, $P < 0.01$] (Fig. 3).

It has been demonstrated that LLI children have a specific deficit in recognizing and distinguishing between brief and rapidly changing sensory events presented within the domain of tens of milliseconds. Tallal and colleagues have hypothesized that this basic temporal processing deficit may disrupt the normal sharpening of neurally represented phonetic prototypes for the native language in LLI children, resulting in a cascade of negative effects on subsequent receptive and expressive language development—and ultimately resulting in a failure to generate the robust phonetic code that is so essential to learning to read. Although previous research has shown consistently significant correlations between the severity of nonverbal temporal processing deficits

Fig. 2. Difference z scores (posttraining minus pretraining) are shown for LLI subjects in study 2 who received speech and language training with either acoustically modified or natural speech. Difference z scores are presented for measures of temporal threshold, speech discrimination (GFW), language processing (Token Test), and grammatical comprehension (CYCLE-R). To facilitate group comparisons across each of the measures, we converted raw scores to z scores on the basis of the pretraining performance of all subjects on each individual test. Mean and standard error values for each measure demonstrate that significantly larger improvements were achieved by the LLI children receiving the acoustically modified speech training (black bars) as compared with the performance improvements recorded for the subjects receiving natural speech training (white bars). The temporal threshold values were converted to positive values for display purposes.



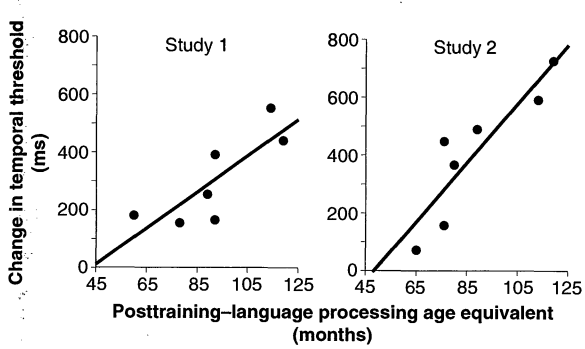


Fig. 3. Relation between the improvement in temporal threshold (*16*) and language processing, as measured on the Token Test, is displayed for the study 1 and study 2 children who received the temporal training and modified speech exercises. Note that data from four subjects in study 2 are not shown in this figure because they failed to reach criterion (75% or greater accuracy) at any stimulus duration either at the pre- or posttraining evaluations on the temporal threshold procedure. For study 1, $r = 0.81$; for study 2, $r = 0.89$.

and various components of language and reading (*8, 17*), these studies were unable to address issues regarding the causality, etiology, or effectiveness of remediation of LLI and temporal processing deficits.

In the current study we have demonstrated that training children with speech stimuli in which the brief, rapidly changing components have been temporally prolonged and emphasized, coupled with adaptive training exercises designed to sharpen temporal processing abilities (*9*), results in a dramatic improvement in receptive speech and language in LLI children. Longitudinal studies with LLI children have shown that these children are not only delayed in the onset of speech and language development, but progress considerably more slowly than normal children in language development, despite conventional therapeutic intervention (*5, 18*). The results of the studies reported here are contrary to this expectation, showing that uncharacteristically rapid growth (approximately 2 years) in receptive speech and language abilities can be achieved by LLI children over a training period of only 4 weeks. We emphasize that significant improvements were demonstrated not only during training with modified speech stimuli, but also generalized to unmodified, natural speech used for pretraining and posttraining test administration. Furthermore, the gains achieved in training were substantially maintained when children were retested 6 weeks after the completion of the training study, suggesting that the perceptual and language skills of these children have been enduringly modified (*19*).

The degree of rapid change in receptive language processing (including receptive phonology, morphology, and syntax), shown here to result from changes made in the acoustic signal of speech and adaptive temporal training (*9*), suggests that the symptomatology of LLI children may reflect primarily bottom-up processing constraints rather than a defect in linguistic competence per se. It seems unlikely that these children learned the equivalent of approximately 2 years of language in 1 month. Rather, it appears that they had already developed considerably more language competence than they were able to demonstrate or use "on line" under normal listening and speaking conditions. This study demonstrates that providing LLI children with access to an acoustically modified signal that they can adequately process, coupled with reducing their temporal processing deficit, achieved through adaptive training (*9*), significantly improves LLI children's subsequent processing of natural "on line" speech. The resulting improvements in the fidelity of their speech inputs result in major and rapid improvements in their speech reception and language comprehension performance.

Preliminary studies suggest that temporal processing abilities can be assessed in the first year of life and that these abilities may predict subsequent language comprehension abilities (*20*). The LLI children participating in the current study were already 5 to 10 years old. Even greater benefits of temporal processing training coupled with exposure to acoustically modified speech during the critical period for speech and language development may be expected to be achieved from earlier intervention, as well as from a longer intervention training period. This training strategy would appear to provide a powerful basis for remediating the speech reception deficits of the many millions of LLI children and adults, as well as the deficits of aged, aphasic, and other special populations whose speech discrimination and language comprehension may be impaired because of an underlying input timing–based speech reception deficit (*21*).

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10. Speech modification was achieved by a two-stage processing algorithm. In the first stage, the rate of the speech signal was prolonged by 50%, while preserving its spectral content and natural quality. This time-scale modification was implemented with a digital signal processing algorithm [M. R. Portnoff, *IEEE Trans. Acoust. Speech Signal Process.* **29** (no. 3), 374 (1981)]. This algorithm involved computation of the short-time Fourier transform (STFT) of the speech signal with the fast-Fourier transform (FFT), linear interpolation, and phase-modification of the STFT to the new time scale, followed by additive synthesis with the inverse-Fourier transform. In the second stage of processing, the fast transition elements were differentially amplified by as much as 20 dB. The fast transition elements of speech were defined as the 3- to 30-Hz components of the speech envelope within rate-changed narrow-band channels. This differential "emphasis" was also implemented with a digital signal processing algorithm. The modification involved band-pass filtering of the speech signal into critical-band channels, computation of the envelope within each channel, band-pass filtering of the speech envelope, modification of the narrow-band signals to carry the new band-pass envelope followed by additive synthesis of the modified speech signal from the narrow-band channels. The above-mentioned algorithm was implemented initially by using a filter-bank summation algorithm and then improved on with the overlap-add procedure and the FFT [T. Langhans and I. I. W. Strube, *Proc. of IEEE–International Conference on Acoustics and Speech Signal Processing* **1982**, 156 (1982)].
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are then presented sequentially in various combinations (that is, 1-1, 2-1, 1-2, and 2-2) with an interstimulus interval (ISI) interposed between the two tones. The subject is required to reproduce the sequence by pressing the panels in the correct order. The Computerized Repetition Test determines the threshold ISI at which sequences of two pure-tone stimuli of 150-, 75-, 40-, or 17-ms duration are perceived and reproduced with 75% accuracy. The ISIs vary from 500 to 0 ms. (v) R. Goldman and M. Fristoe, *Goldman-Fristoe Test of Articulation* (American Guidance Service, Circle Pines, MN, 1986). The Sounds-in-Words subtest was used to assess accuracy in speech articulation. Speech was elicited by having the child label a picture that depicted a common object or activity.

13. The speech and language exercises were developed as games to maintain attention and motivation over the course of the study. Tape recorded syllables, words, phrases, and sentences that had been acoustically modified with the speech algorithm developed for this study were presented to the child over headphones or free field. The games included acting out commands in a Simon Says format with props; pointing to pictures or colored blocks in response to commands; repeating verbatim syllables, nonsense words, real words, or sentences; and pointing to pictures corresponding to spoken words. Throughout training, commands of increasing length and grammatical complexity were used in these games. Careful attention was given in the design of the listening exercises to ensure that foils developed for each item would focus the attention of the child on the salient aspects of speech discrimination or receptive grammar being trained. In the listening games, regardless of the accuracy of the child's response, immediate nonverbal feedback was given after each response ("thumbs up" or "thumbs down"), followed by a repetition of the item with the correct response indicated by the clinician, so the child could have a second chance to process correctly. Each child won points for cooperation throughout the training, which were tallied daily and exchanged for prizes at the end of each week.
14. Changes from study 1 to study 2 included (i) increasing the duration of the laboratory sessions from 3 to 3.5 hours per day, (ii) providing homework solely in the form of recorded children's stories on tape [either acoustically modified (group A) or with natural unmodified speech (group B)] instead of computer games, (iii) increasing the number of computer game formats from two to four, and (iv) modifying the ratio of clinicians to children in each training session from one-to-one to usually one-to-one, but on occasion one-to-two. The children in study 1 and group A in study 2 received computer games that adaptively trained temporal processing and phoneme perception, whereas the children in group B study 2 received the same schedule of computer game training and reinforcement, but with games that did not contain temporally or phonetically adaptive stimuli.
15. Subjects were assigned to the two groups to minimize the differences between subjects on measures of performance IQ (PIQ) [*Wechsler Intelligence Scale for Children-III* (The Psychological Corporation, New York, 1991)] reported as mean (SEM) [PIQ, group A = 96.1 (2.6), group B = 96.6 (3.3)], and receptive language performance (Token Test Age scores) reported as mean (SEM) [group A = 5.4 (0.4), group B = 6.1 (0.7)].
16. Previous studies [P. Tallal and M. Piercy, *Neuropsychologia* **11**, 389 (1973)] have shown that the total signal duration of auditory stimulus patterns, as indexed by the relation between the duration and interval among stimulus elements, is critical for demonstrating the temporal processing deficits of LLI children. In the present investigation, temporal threshold values were calculated as the sum of the minimal tone durations (150-, 75-, 40-, or 17-ms tone pairs) and the average ISI based on an adaptive staircase (two-up and one-down) procedure to which subjects were able to reproduce pairs of tone sequences by pressing a response panel. A performance level of 75% or greater accuracy was required at a particular stimulus duration before a threshold would be calculated. The average pretraining thresholds by the LLI children were 491 ms in study 1 and 287 ms in study 2 (9). Normally developing children of a comparable age have been shown to require ISIs of less than 20 ms on this test (5).
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19. Six weeks after training was completed in study 1, six of the seven children were retested with the same battery of benchmark speech and language measures to determine the extent to which the significant gains made between pre- and posttraining were maintained, without further exposure to acoustically modified speech. The results showed that the significant improvements over pretraining baseline scores were maintained.
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Molecular Orientation and Two-Component Nature of the Crystalline Fraction of Spider Dragline Silk

Alexandra H. Simmons,* Carl A. Michal, Lynn W. Jelinski†

The molecular origin of the exceptional mechanical properties of spider silk is unclear. This paper presents solid-state ^2H nuclear magnetic resonance data from unoriented, oriented, and supercontracted fibers, indicating that the crystalline fraction of dragline silk consists of two types of alanine-rich regions, one that is highly oriented and one that is poorly oriented and less densely packed. A new model for the molecular-level structure of individual silk molecules and their arrangement in the fibers is proposed. These data suggest that it will be necessary to control the secondary structure of individual polymer molecules in order to obtain optimum properties in bio-inspired polymers.

Spider dragline silk is nature's high-performance fiber. A unique combination of tensile strength and elasticity gives the silk a higher energy to break than that of other natural or synthetic fibers, which is essential for its structural role in a spiderweb's frame and its function of supporting a dropping spider. It is known that dragline silk is a semicrystalline polymer, but the amount, composition, orientation, and structure of each of its phases remain the subject of debate. An early study of fibroins, including the silk of *Nephila madagascarensis*, showed that they could be grouped on the basis of their tensile behavior (*1*). The ratio of long-side-chain to short-side-chain amino acids in these protein polymers is similar for samples within a group. X-ray diffraction analysis of *N. madagascarensis* silk showed that the crystalline regions were composed of antiparallel pleated sheets (*2*). The relative amount of crystalline to amorphous content was thought to be high due to the preponderance of small amino acids, which pack efficiently. Warwicker placed the silk in a group containing fibroins with the same lattice spacing as β-polyalanine (*2*). He proposed that bulky residues reside in amorphous regions, as their side chains cannot be accommodated in the crystalline domains.

In 1977, Work discovered that wetting of unrestrained fibers of spider dragline silk at room temperature causes them to contract to half their initial length (*3*, *4*). In synthetic fibers, such supercontraction occurs only at extreme temperatures or in harsh solvents. Supercontraction of dragline fibers is accompanied by a decrease in tensile strength and an increase in elongation before breaking; fibers recover their original mechanical properties when dried. Interplanar spacings in crystalline regions of *N. clavipes* major ampullate silk do not change on supercontraction (*5*). Dry dragline silk has a predicted crystallinity of 30% (*6*).

Early data identified an ampullate protein of *N. clavipes* with a molecular weight greater than 200 kD (*7*, *8*), whereas more recent data (*9*) suggest that the freshly synthesized protein in the gland may be as large as 720 kD. Amino acid analysis has shown that, like silkworm silk, dragline silk contains not only

Center for Advanced Technology in Biotechnology, 130 Biotechnology Building, Cornell University, Ithaca, NY 14853, USA.

*Present address: DuPont Canada, Research and Development Centre, Kingston, Ontario, Canada K7L 5A5.
†To whom correspondence should be addressed.