CHAPTER

Fast ForWord®: The Birth of the Neurocognitive Training Revolution

7

Paula Tallal[1]

Rutgers, The State University of New Jersey, Center for Molecular and Behavioral Neuroscience, Newark, NJ, USA

[1]*Corresponding author: Tel.: 619-417-4149; Fax: 973-353-1760, e-mail address: tallal@andromeda.rutgers.edu*

Abstract

In 1996, I cofounded Scientific Learning Corporation (SLC) with Drs Michael Merzenich, William Jenkins, and Steve Miller. I coined the term "Cogniceutical" to describe the new type of company we envisioned. SLC was the first company cofounded by academic scientists with the mission of building neurocognitive interventions. *Fast ForWord*® is the registered trade name of the platform SLC built to translate basic neuroplasticity-based training research into clinical and educational products. *Fast ForWord*® was the first cognitive neurotherapeutic intervention, the first to be individually adaptive in real time, the first "brain fitness" program that collected data over the Internet, and the first to use computer gaming technologies to change brains and enhance human potential. We included lofty goals in our first business plan for SLC. These included: using neuroplasticity-based training to improve language, literacy, and other academic skills; helping seniors maintain and recover function; helping people learn English as a second language; helping patient populations with neurological or mental disorders. SLC's first focus became improving language and literacy. Mike, Bill, Steve, and I began this journey together in 1994 with a laboratory-based research study that included seven children. To date, over two million children in 46 countries have used Fast *ForWord*® products. On any given school day, approximately 60,000 children log in to train on 1 of 10 *Fast ForWord Language*, *Literacy*, or *Reading* programs. We did not know at the time that we were creating what became a "disruptive innovation." This chapter chronicles this transformational journey.

Keywords

neurocognitive training, video games, language, literacy, reading, language-learning impairments, neuroplasticity-based training, dyslexia, autism, *Fast ForWord*®:, Scientific Learning Corporation

Progress in Brain Research, Volume 207, ISSN 0079-6123, http://dx.doi.org/10.1016/B978-0-444-63327-9.00006-0

1 INTRODUCTION

Fast ForWord® grew out of over 25 years of basic and clinical research in two distinct scientific disciplines. One utilized behavioral, electrophysiological, and neuroimaging methods to study individual differences in language development and the etiology of developmental language-based learning disabilities (including specific language impairment (SLI), autism, and dyslexia). The other utilized neurophysiological methods in animals to study neuroplasticity, that is, changes at the cellular level driven by behavioral training techniques. This chapter reviews (1) how these two lines of research were integrated to form the scientific basis of *Fast ForWord®* (and subsequently its sister product Posit Science Corporation's *Brain Fitness Program®*), and (2) the steps taken to translate and instantiate our integrated laboratory research into clinical and classroom interventions that could be scaled up for distribution around the world, while remaining efficient and effective.

When we began our collaboration in 1993, the now rapidly growing fields of "cognitive neurotherapeutics" and "neuroeducation" did not exist. The concept of using neuroplasticity-based training to improve "brain fitness" in humans did not exist. Few clinics or schools had computers and fewer still had Internet access. The methods we developed which subsequently were the basis of over 50 patents were the first to use video gaming technologies with the explicit goal of improving human performance. Over the past 17 years since inception, Scientific Learning Corporation (SLC) has developed a large series of perceptual, cognitive, language, literacy, and early math training exercises, "disguised" as interactive, individually adaptive, computer games, trademarked *Fast ForWord®*. SLC products, now delivered over the Internet, include a wide variety of individually adaptive assessment and intervention exercises that provide real-time feedback and rewards as well as ongoing, electronic data analysis and detailed reporting to the end user. A sister company, Posit Science Corporation, cofounded by Dr Michael Merzenich, delivers similar products to aging adults and adult patient populations. Posit's first product, *The Brain Fitness Program®*, adapted several of the original *Fast ForWord®* auditory processing, verbal memory, and language comprehension exercises, including the use of acoustically modified speech.

2 INTEGRATING RESEARCH ON LANGUAGE DEVELOPMENT AND DISORDERS WITH NEUROPLASTICITY RESEARCH

It is generally assumed that most children develop language automatically, with no need for explicit instruction. However, prospective, developmental studies have shown that there are quite substantial individual differences in language development driven by a wide variety of genetic, environmental, and sociocultural factors (Bates and Tomasello, 2001; Heim and Benasich, 2006). As such, millions of children enter school with weak *aural* receptive and/or expressive language skills. Prospective longitudinal research has shown that entering formal education with weak language skills, especially poor language comprehension, places a child at increased risk for a cascade of negative life outcomes (Hart and Risley, 1995). Despite the critical role aural language plays in academic success, with over 80% of classroom instruction presented *aurally*, it is remarkable that there is little if any formal school curriculum focused explicitly on receptive (comprehension) and expressive (spoken) language development. Rather, early education focuses on teaching *written* language (reading, writing, spelling). During the preschool years the focus is on "reading readiness." Once formal education begins, if a child begins to struggle, intervention is focused on reading. Put simply, schools are in the business of teaching a child to learn to read, not to talk or listen. However, if our ultimate goal is to improve literacy outcomes, what is needed is a better scientific understanding of how the brain learns to process and produce language, how language forms the foundation upon which literacy skills depend, and how to effectively transfer this scientific knowledge to clinics and classrooms in the form of effective and efficient intervention tools. *The Fast ForWord®* series of training programs (there are currently 10 products, including *Fast ForWord® Language*, *Literacy*, and *Reading Levels 1–5*) was developed to address this need.

The most basic unit of any language is the phoneme, the smallest unit of sound that can change the meaning of a word. For most languages, in order to learn how to read and become a proficient reader, the child must become aware that words can be segmented into smaller units of sound (phonemes) and it is these *sounds* that the letters represent. This is referred to as *phonological awareness*. Phonemes are the basic building blocks for both spoken and written language. Not surprisingly, phonological skills have been shown to correlate both prospectively as well as concurrently with both aural and written language ability throughout life (Tallal, 2004). To improve literacy outcomes, we need to understand the *language to literacy continuum*, and how at a fundamental level phonemes of a language come to be organized or "represented" in the brain. As phonemes are, themselves, comprised of smaller, dynamically changing, acoustic spectrotemporal features, the role that complex auditory processing plays in the development of phonological systems has been a major topic of research, and one that was fundamental to the design of the series of *Fast ForWord® Language and Literacy* products.

As is the case in all other sensory modalities, the acoustic information within the complex waveform of speech can be broken down into distinct physical features (frequency, duration, amplitude), each of which is represented in fine grained detail in the auditory system (Kraus et al., 1995, 1996). According to Hebb (1949), when a complex signal occurs, all of the neurons that are activated by this complex set of features, per unit time, fire together. The likelihood that a particular pattern will come to be represented increases with each additional exposure of a firing pattern ensemble. It has been increasingly documented that phonological systems are developed through exposure to the native language(s) (Kuhl et al., 1997). Each language has its own set of phonemes that must be learned from experiencing repeating acoustic patterns within the ongoing speech waveform. As infants are exposed to a continuous speech stream from the environment, they must parse the incoming acoustic signal into consistent, replicable chunks of time that occur in statistically predictable sequences (Saffran, et al., 1996). It is hypothesized that when sensory inputs enter the nervous system differentially in time, the neuronal representation 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 (Wang et al., 1995). 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 phonological percepts (Tallal, 2004). For speech, statistically consistent acoustic patterns occur frequently and consistently within the ongoing acoustic waveform in chunks of various durations. Chunking within the tens of milliseconds (ms) time window will allow for the fine grain analysis needed to represent the acoustic differences between individual phonemes such as /b/ and /d/. Chunking over longer periods of time (hundreds of milliseconds) will result in firing patterns consistent with syllable length representations (Hickok and Poeppel, 2007). It is these chunks of acoustic information, which form the building blocks for language, that can be infinitely combined to form both spoken and written words. Furthermore, based on optimal control theory (Todorov, 2006), it is hypothesized that similar unsupervised statistical learning processes are at play for learning how words are combined to form sentences that are consistent with the specific grammatical rules that govern how each language is constructed.

While most children develop language without the need for explicit training, a growing number of children are entering formal education without sufficient language skills to support proficient written language and literacy development. Children who fall within the lower end of the continuum of individual differences in language development are diagnosed as having "language-based learning disabilities." In addition to linguistic studies that focus on describing the differential pattern of language development in these populations of children (Leonard, 1998), research has focused on delineating basic domain-general sensory, motor, and cognitive deficits that consistently co-occur with language impairments (Tallal et al., 1993). In 1973, I reported for the first time that children with developmental language impairments were significantly impaired in both discriminating and sequencing two brief (75 ms) complex tones differing in fundamental frequency when they were separated by an inter-stimulus-interval (ISI) of 150 ms or less, but performed as well as age-matched controls with longer duration ISIs (Tallal and Piercy, 1973). In a series of follow-on papers, we showed that this deficit in "rapid auditory processing" (RAP) extended to verbal stimuli that incorporated similarly brief, rapidly successive acoustic cues that are critical for speech identification and discrimination (Tallal and Piercy, 1974, 1975). For example, the major cue for stop-consonants is the rapidly changing frequency spectrum of the second and third formant transitions that is not only transitional but also of short duration (approximately 40 ms). We hypothesized, and subsequently demonstrated, that rather than being impaired in all aspects of speech perception, children with developmental language impairments are selectively impaired only in identifying and discriminating between those speech sounds that depended on the processing of brief, rapidly successive acoustic cues. To further specify the nature of this deficit, we used computer speech synthesis to control the exact duration of acoustic cues *within* speech syllables (intrasyllabically). Specifically, we extended the duration of the formant transition within the syllables /ba/ and /da/ from 43 to 95 ms. The results of this study showed, for the first time, that not only were children with SLI selectively impaired in discriminating the brief duration of the discriminable components within speech syllables but that their perception could be virtually normalized by *extending in time* these brief duration acoustic cues. Subsequent studies in our own and many other labs in the ensuing 20 years showed that there is a highly significant correlation between a language impaired child's RAP performance (as measured by the ISI needed between two brief nonverbal tones) and (1) their speech perception and production abilities, (2) their language comprehension abilities, and (3) their phonological awareness abilities as measured by their nonword reading abilities (Stark and Tallal, 1988; Tallal, 2004). In subsequent prospective longitudinal studies beginning in infancy, we showed that the single best predictor of verbal IQ in toddlers (36 months old) was their RAP threshold (as measured by the ISI needed between two brief nonverbal tones) established when they were infants (Benasich and Tallal, 2002). Importantly, infants' RAP thresholds did not predict subsequent nonverbal IQ, demonstrating the specificity of the relationship between RAP and language development. Remarkably, out of a large battery of perceptual and cognitive tests, RAP thresholds established at 6 months of age proved to be the single most powerful variable that, when combined with gender, predicted 94% correctly those children who would score in the "impaired" range on the Stanford Binet Verbal IQ test by age 3 years.

3 INTEGRATING NEUROPLASTICITY-BASED TRAINING RESEARCH WITH RESEARCH ON INDIVIDUAL DIFFERENCES IN LANGUAGE DEVELOPMENT

Neurophysiologists have mapped the features of the sensory world at the single cell level. This research has shown that within each sensory modality, the features that represent the physical world come to be mapped at the cellular level in a highly organized fashion. For example, in the auditory modality, there is a tonotopic representation of frequency such that cells that fire to a specific frequency are located physically adjacent to cells that fire to the next higher frequency, in a continuous manner throughout the frequency range (Clopton et al., 1974). In addition to tonotopic (frequency) representation in A1, there are neurons that code selectively for temporal features of sound (Eggermont, 1981), as well as "inseparable" temporospectral combinations such as frequency sweeps similar to those occurring within formant transitions of speech (Orduna et al., 2001). That these sensory maps must be learned from environmental exposure is evidenced by neurophysiological research, showing the effects of sensory deprivation or alteration (Neville, 1985). Exposure to altered acoustic input during critical periods of early development, for example continuous or pulsed noise, significantly disrupts the development of tonotopic representation in primary auditory cortex, and these developmental changes continue to be evident into adulthood. Merzenich and colleagues have shown that beyond this early period, sensorineural maps can no longer be altered by mere exposure. Rather, alteration of neural maps requires active attention to highly repetitive and explicit input features in the context of an intensively trained, individually adaptive task, with timely feedback and reinforcement of correct responses (Chang and Merzenich, 2003; Recanzone et al., 1993; Zhang, et al., 2001). This form of training is referred to as *neuroplasticity-based training*.

4 THE BIRTH OF *FAST FORWORD*®: TRANSLATING THEORY INTO PRACTICE

Considering the amount of speech directed to the infant, it is easy to understand how important speech is in shaping the auditory cortex during critical periods of human development. Furthermore, adult speech to infants (known as "parentese") has been shown to exaggerate (extend in time and amplitude enhance) the acoustic changes that differentiate phonemes within syllables and words (Liu et al., 2003). Three decades of research with children with developmental language and literacy impairments has shown that these children are at high risk for having specific deficits in processing the brief, rapidly successive, temporospectral cues within ongoing speech (Tallal, 2004). Furthermore, we demonstrated as early as 1975, using computer-synthesized speech syllables, that language impaired children's perception could be substantially normalized, at least at the single syllable level, by extending in-time rapid temporospectral, intrasyllabic cues (Tallal and Piercy, 1975). We hypothesized that this acoustic modification of the temporospectral cues within computer-synthesized speech may play a similar role as "parentese" in helping children segment and process the rapid temporospectral cues within ongoing speech, well beyond the critical period. Unfortunately, it took 20 years before technological advances made it possible to develop a speech algorithm that could make similar *intrasyllabic* acoustic alterations in real time within ongoing speech (Nagarajan et al., 1998). During that same period of time, research demonstrating not only that the brain was highly plastic well beyond the critical period but also elaborating the precise "scientific learning principles" needed to most efficiently and effectively drive neuroplasticity-based training, came of age (Jenkins et al.,1990). Cortical plasticity and learning studies conducted in primate and human models had shown that such training (1) had to be applied with a heavy schedule of practice trials (repetition, repetition, repetition), (2) spaced across a series of successive training days, (3) had to individually adapt along easy to harder trajectories to drive continuous performance improvements, and (4) would have to be conducted under conditions of high motivational drive with timely rewards (Merzenich and Jenkins, 1998).

In 1993, the Tallal lab at Rutgers University, Newark began collaborating with the Merzenich lab at UCSF. We began with parallel research goals: (1) to determine whether basic nonverbal auditory temporal thresholds could be improved (decreased) in human children, specifically those with language-learning impairments (LLI) that were characterized by RAP deficits; (2) to develop a speech processing algorithm that would selectively find, amplitude enhance, and extend in time (*acoustically modify*) the most rapidly changing acoustic changes (3–30 Hz) that occurred in real time within ongoing speech (see Nagarajan et al., 1998 for details); and (3) to determine if training children with LLI to process basic auditory temporospectral cues faster, while simultaneously training speech and language skills using this *acoustically modified speech*, would lead to improvements in speech and/or language abilities. Specifically, we hypothesized that the "scientific learning principles," that had been shown in studies with monkeys to drive neuroplasticity in sensory maps, might be adapted for use with children with LLI to ameliorate their rate processing constraints. Simultaneously, we hypothesized that we would be able to improve aural language skills by training a wide variety of linguistic skills using acoustically modified speech. However, rather than having children depend on acoustically modified speech for improved speech processing, our aim was to develop neuroplasticity-based training procedures that would individually adapt, based on a child's linguistic performance, from the acoustically modified "slowed down" speech to natural "fast" speech. Specifically, a hierarchy of training exercises, "disguised" as games (that ultimately evolved into a series of computer/Internet base training programs marketed under the trade name *Fast ForWord® Language*) was developed to (1) attempt to drive neural processing of rapidly successive acoustic stimuli to faster and faster rates; (2) attempt to improve foundational cognitive skills such attention, memory, and sequencing; and (3) improve speech perception, phonological analysis and awareness, and language comprehension. We aimed to do this by providing intensive daily 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 intrasyllabic cues within ongoing speech.

5 DESIGNING NEUROPLASTICITY-BASED TRAINING GAMES

For our first study, we designed and developed a series of verbal training exercises ranging from speech discrimination to grammatical comprehension, disguised as "games." Some of these games were implemented on computers, while trained professionals using tape-recorded stimuli presented others. In addition to explicitly training perceptual and linguistic skills, all were developed in a training format that also aimed to simultaneously increase foundational cognitive skills including auditory attention, speed of processing, sequencing, and memory span. For example, as seen in Fig. 1A, one of the speech processing exercises was designed in the format of a "concentration game." In this game, a series of squares were laid out on the computer screen in a visual grid. When each square was clicked, a syllable was presented acoustically. The goal of this game was to find two syllables that matched. When

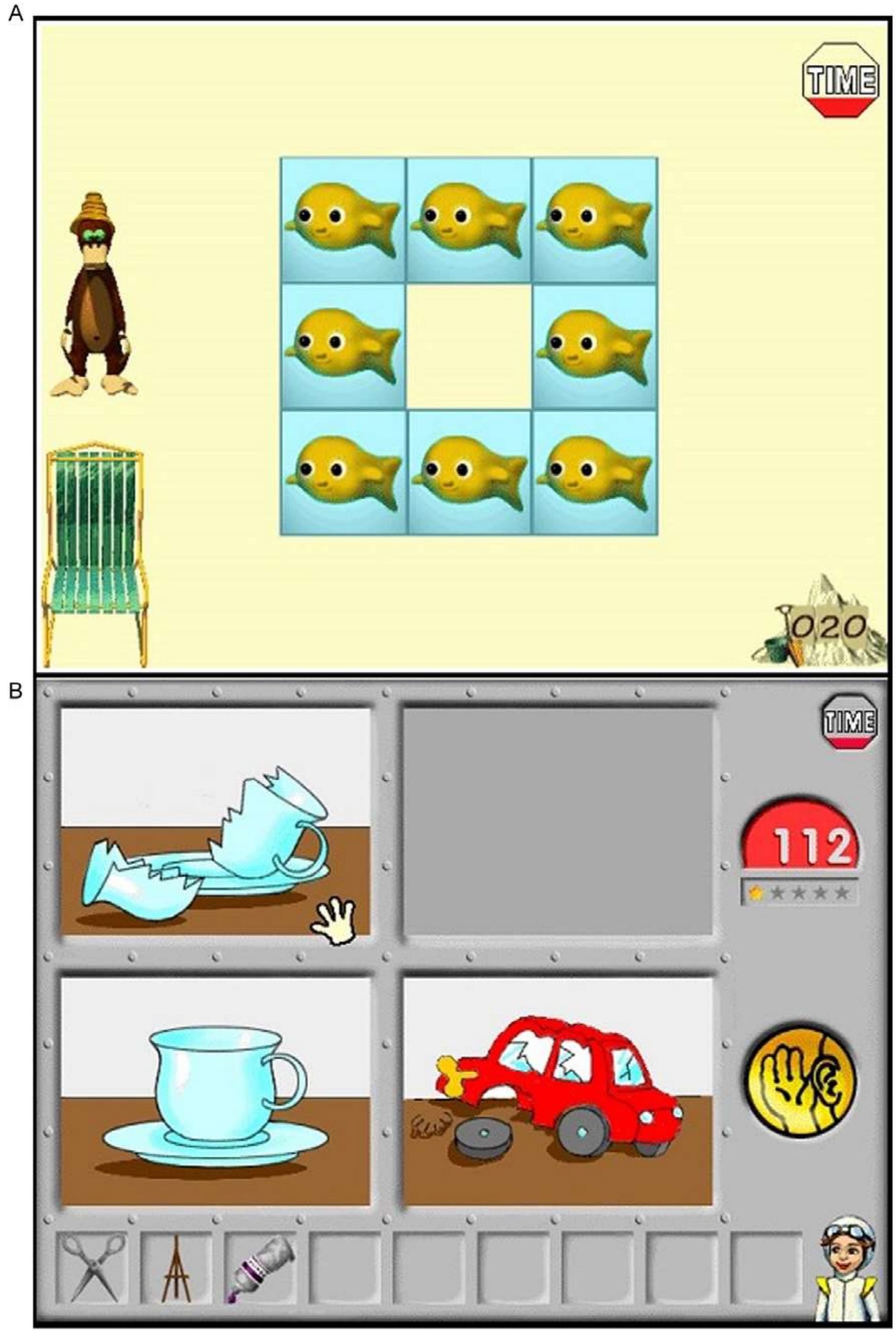

FIGURE 1

Screenshots from two Fast ForWord® Language V1 games are shown. (A) One of the speech processing exercises (phonic match) that was designed in the format of a "concentration game."

clicked sequentially they would disappear. To enhance attention, memory, and motivation, bonus points were given when the screen was cleared with the fewest number of clicks. The task began at an easy level, with only four squares and two pairs of syllables that were acoustically easy to discriminate. As each player progressed, the number of squares in the grid increased (memory training) while the acoustic difference between syllables decreased (speech discrimination training). Thus, both speech discrimination and memory skills were simultaneously being trained and individually adapted. Another exercise was presented as a board game with colored circles and squares. Children pressed an orienting button to receive a command. Commands, initially presented with the highest degree of acoustic modification, began at a very easy level such as "touch the red square." As a child progressed through the game, the number and size of circles and squares presented, as well as the difficulty of the commands, increased based on each participant's trial-by-trial response. The goal was to present commands of increasing length and grammatical complexity, such as "Before touching the large blue circle, put the small red square between the large white square and the large blue square." As participants advanced, the degree of acoustic modification decreased back to normal, fast speech. This exercise "cross-trained" sustained attention, sequencing, serial memory, and grammar in

FIGURE 1—Cont'd In this game, a series of squares with the same picture on them are laid out on the computer screen in a visual grid. When each square is clicked, a syllable is presented acoustically. The goal of this game is to find two syllables that match. When clicked sequentially these two squares disappear. Bonus points, as indicated by the point counter bottom right of the screen, are given when the screen is cleared with the fewest number of clicks. To indicate this, the "progress creature" on the left begins at the top of the screen and moves toward the chair with each successive click. The task begins at an easy level, with only four squares and two pairs of syllables that were acoustically easy to discriminate. As each player progresses, the number of squares in the grid increases (this screenshot shows nine squares) while the acoustic difference between syllables decreases. (B) The game Language Comprehension Builder adapted from Curtiss and Yamada Comprehensive Evaluation of Language (CYCLE®, 2013) to train each role of English grammar. To initiate a trial, a participant clicks on the hand on the ear button to indicate that they are ready to listen. A command is presented acoustically, in this example, "Point to, the cup is broken." One correct picture and two or three foils were carefully designed to assure that comprehension of a specific grammatical rule, not just vocabulary, is required to answer each command correctly. Correct responses are rewarded by a "ding" sound and winning of a sticker along the bottom and a point is added to the point counter. Incorrect responses are indicated by a "clunk" sound, the command is repeated, and the correct picture is highlighted. After each row of 10 stickers at the bottom is completed, additional reward in the form of bonus points and an equivalent number of "ding" sounds are given. To assure that memorization of commands does not occur, the same set of picture is also used for the command, "The cup is not broken." From Scientific Learning Corporation.

the context of listening comprehension. Yet another exercise (shown in Fig. 1B) was designed to train English grammatical rules. The commands used in this game were licensed from the Curtiss and Yamada Comprehensive Evaluation of Language (CYCLE ©). We adapted this comprehension assessment that was based on years of laboratory research on the progression of normal and delayed language development (Curtiss and Yamada, 2013) into a training exercise designed to train the rules of English grammar. These speech discrimination and language exercises were developed to be individually adaptive; the goal being to find for each child a level of cognitive and linguistic functioning that could be responded to at a high rate of accuracy (approximately 80% correct). As the exercise progressed, the goal was to move toward more rapid and less amplified, natural speech following correct linguistic responses or back to easier (more acoustically modified speech) following incorrect responses.

In addition to the speech discrimination and language comprehension exercises, one game was designed to increase the speed of auditory processing. This computer game used adaptive training with the goal of driving more efficient (shorter) temporospectral integration thresholds for rapidly successive acoustic sweep tones (computer-generated tones that sweep from either high frequency to low frequency, or low to high). To increase generalization across the entire frequency range of speech, three different frequency ranges were selected that covered the frequency range of human speech. As a child progressed in this game, the sweep tone stimuli were individually adapted to decrease in the duration of the tones, the ISI between tones, and the slope of the sweeps, based on each child's trial-by-trial performance. The overarching goal of these combined verbal and nonverbal training exercises was to drive, through adaptive training, each child into the normal processing rate of tens of milliseconds (the range important for phoneme perception) while simultaneously increasing each child's ability to process more complex linguistic structures.

6 THE FIRST LABORATORY STUDIES: RUTGERS SUMMER CAMPS 1994–1995

Two initial laboratory studies were conducted with children who each met the criteria for LLI. These children had normal nonverbal intelligence (85 or above), with language ability at least 1 year behind (see Merzenich et al., 1996 for subject details). The goal of these first studies was to determine (1) if training in rapid tone sequencing would result in increased speed of auditory processing, and (2) if speech discrimination and language comprehension abilities improved more when they were presented with acoustically modified speech than with normal speech. The first study was a feasibility study with seven LLI children. The second study, run as a summer camp, included 22 children with SLI who were *quasi-randomly* assigned (match on age, nonverbal IQ, and degree of language impairment) to either an Experimental ($N=11$) or Control ($N=11$) group. The Experimental group received the language training exercises with acoustically modified speech, while the Control group received the exact same language training, but with natural speech. As such, this study allowed a direct evaluation of whether or not there was added value of providing speech language training with the acoustically modified speech. Furthermore, the Experimental group played the computer game designed to improve RAP skills, while the Control group played a visual computer game for an equivalent period of time that did not require rapid processing and was not temporally adaptive. The camp ran for 6 weeks. In weeks 1 and 6, all subjects received a battery of standardized tests (pre- and post-training measures, respectively). They then received training 5 days a week for 4 weeks. Training sessions were intermixed with breaks for snacks, outdoor games, and art activities. Both groups participated together in the same "computer camp" and received the same amount of training, reinforcement, homework (listening to an audio storybook either with or without acoustically modified speech), and rewards for performance. This allowed a direct control for other potential variables that could have an effect on performance such as test–retest effects, Matthew effects, regression to the mean, etc.

The results of these experiments were published in two back-to-back papers in *Science* in 1996. The language results are reported in Tallal et al. (1996). Traditionally, few children with language-learning impairments receive more than one or two short (30–60 min) sessions of individual or group speech therapy per week and little progress is expected to occur within only 4 weeks of clinical intervention. In contrast, results from this study demonstrated that the rigor, scope, and consistency of the training (100 min, 5 days per week for 4 weeks) resulted in highly significant improvements in speech discrimination, language processing, and grammatical understanding for *both* groups of children. This result has important clinical implications for the intensity of speech therapy that needs to be provided for children with language-based learning disabilities. However, in addition to showing the benefit of more intensive language intervention, this controlled laboratory study also demonstrated the added benefit of providing language instruction using *acoustically modified speech*. Results showed that the Experimental group who received language intervention training *with* acoustically modified speech demonstrated *significantly better outcomes* in speech discrimination, language processing, and grammatical understanding than the Control group who received the same language intervention, but with natural (unmodified) speech.

An accompanying paper published in the same issue of *Science* reported the results of the nonverbal rapid auditory sequencing training that the Experimental group received for 20 min a day, 5 days a week for 4 weeks (Merzenich et al., 1996). This study showed for the first time that basic auditory thresholds are highly modifiable in human children by behavioral training. Importantly, this study also showed that the measured improvement in a child's auditory temporal threshold for correctly segmenting and sequencing successive nonverbal auditory sweep tones was significantly correlated with post-training outcomes in real-time language processing ($r = 0.81$, $p < 0.05$). That is, the amount of improvement a child made in nonverbal auditory processing speed was highly correlated with the amount of improvement that child made in language comprehension.

These controlled laboratory studies demonstrated the immediate efficacy of this novel training approach. However, it was also important to determine the longer term effectiveness of this brief, but intensive, training. To address this question, the LLI children were assessed again at 6 weeks as well as 6 months after training had concluded (Bedi et al., 1999). Results of these follow-up studies showed that all children continued to make progress relative to their performance after 4 weeks of training. Furthermore, the children with LLI who received the experimental training protocol continued to perform significantly better than children who received the treatment control conditions. The Experimental group not only maintained their initial gains but also continued to improve at an accelerated pace compared to the control group during the 6 weeks following the conclusion of the program. These significant improvements and group difference were maintained out to 6 months. These results provide strong evidence for the longer term efficacy of this new training approach.

As might be expected, these early reports of highly positive increases in language scores in children with language-learning deficits led to considerable excitement in both the scientific and clinical communities as well as the general public. We had thousands of requests to "send the CD." Of course, there was no CD to send at this stage! However, our results did suggest that what we had developed had considerable practical applications. Our Universities' Technology Transfer Offices, which owned our intellectual property and had submitted patents disclosures based on it, guided us as to how to proceed to translate our research out of our labs and into public use. It quickly became clear that what we had begun to develop was something completely new. If we aimed to translate our research into the public domain, we would need to start our own company. And so, in 1996, together with my research collaborators, Drs Michael Merzenich, William Jenkins, and Steve Miller, we cofounded Scientific Learning Corporation. Our goal was to figure out how to scale up and deliver cognitive, neuroplasticity-based, individually adaptive training programs to individuals around the world, while still maintaining efficacy.

7 SCALING UP: THE "NEUROTHERAPEUTIC REVOLUTION" *FAST FORWORD® LANGUAGE VERSION 1 (V1)*

7.1 First Multisite Clinical Field Trial (1996–1997)

It is one thing to obtain results in well-controlled studies in a research laboratory under the direct supervision of skilled research scientists. It is quite another to demonstrate that efficacy can be achieved in real-world clinics and classrooms where children most commonly receive intervention. Soon after founding SLC, our first goal was to convert the games used in our laboratory studies into a fully computerized training program and then to conduct large-scale field trials in clinical and educational settings to assess its efficacy. The purpose of this trial was to determine whether the efficacy that was demonstrated in the laboratory could be replicated in clinics and classrooms with fully computerized exercises, under the supervision of clinicians and teachers (rather than trained researchers). In addition, in order to assure consistency in program delivery, data collection and analysis, and quality control across multiple sites and long distances, the computerized adaptive training programs were created in the form of a CD-Rom. Our next hurdle was to figure out how to monitor the implementation of the program remotely, and interact with the professionals delivering it to children at many different sites simultaneously across days, weeks, and months. In this first version of what became *Fast ForWord*® *Language*, trial-by-trial responses for each of the seven exercises in the program were recorded on the hard drive of the computer each child used to play the games. These responses were sent daily, protected by individual client ID numbers, over the Internet to SLC where they are analyzed, tabulated, and immediately returned electronically to the professional supervising the training. We recruited licensed speech language pathologists (SLPs) who were interested in collaborating with us to provide this novel intervention in their clinic or classroom to children who met the criteria as LLI. We developed a 2-day, hands-on training workshop for SLPs that covered the study design, subject selection inclusionary and exclusionary criteria, how to set up the training on their own computer, how to upload and download the data they were going to collect over the Internet, how to help children who might be struggling to progress in the various exercises, and how to keep children motivated throughout the daily exercises that were to be delivered for 100 min a day, 5 days a week for 4–8 weeks. What we had not anticipated, and what turned out to be the most difficult early barrier to translating *Fast ForWord*® *Language* to real-world settings, was that few SLPs in 1996 had a computer in their clinic or classroom, and virtually none had an Internet connection! Thus, for many of our collaborating schools and clinics, *Fast ForWord*® was their first experience using computer/Internet technology.

Clinicians who volunteered to participate in this field trial were encouraged to select a battery of standardized central auditory processing, speech, and language tests that they used most commonly in their own clinical practice to assess children with LLI. Children who were receiving speech therapy and scored at least one or more standard deviations below the mean in the area of central auditory processing, speech discrimination, and/or language comprehension were eligible for inclusion. Case history records indicated that children who met these study criteria had one or more of the following diagnostic classifications: SLI, attention deficit disorder, pervasive developmental disability, autism, central auditory processing disorder (CAPD), dyslexia, or learning disability.

The first field trial included over 500 children aged 4–14 identified by 60 professionals at 35 clinical or educational sites. At each site, these independent speech language professionals collected all of the pre- and poststandardized test data as well as administered the *Fast ForWord*® *Language* training program to students who met the study criteria. The goals of this first field trial were to determine (1) whether or not the results obtained in the laboratory could be replicated by clinicians who most often treat children with language-based learning problems; (2) whether the result would generalize to a broader population of children with a variety of speech, oral, and written language and/or CAPDs; and (3) whether efficacy would generalize to the wide variety of standardized tests that are most commonly used clinically. This first field trial was *not* designed to be a controlled study, but rather a "proof of concept" for scaling up this novel approach for clinical and education settings while still maintaining efficacy in terms of improved language functions. This is important because if the training failed to improve language outcomes in the hands of clinicians in the field, this would have indicated that the basic methods we were planning to use to scale up our research were not effective in field settings. However, if the results did replicate those found in the controlled laboratory studies, we could proceed to further scale up in the field, as a randomized control trial had already demonstrated that the method was effective in the laboratory. A summary of results from this first field trial are presented in Miller et al. (1999), comparing pre-Fast ForWord training standardized test scores to post-test standard scores. On average, the 35 sites reported convincing evidence that clinicians can be trained to provide *Fast ForWord® Language* in their clinics and classrooms according to the prescribed protocol. Specifically, 90% of the children experienced significant gains in one or more tested areas. Most children made significant gains in multiple areas, including central auditory processing, phonemic awareness, listening, speaking, attention, language fundamentals, grammar, and ability to follow directions. On average, children advanced 1–2 years, based on standardized tests, following 4–8 weeks of *Fast ForWord® Language* participation. Significant improvement was obtained in areas targeted by *Fast ForWord® Language* training. In addition, results showed that efficacy *generalized beyond areas directly trained* to include improved expressive (spoken) language abilities as well as some early reading (phonological awareness) abilities, despite the fact that no letters were included in any of the *Fast ForWord® Language* exercises. Importantly, this finding demonstrated that these methods not only improved skills that were directly trained but also generalized to related skills that were not directly trained.

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 2 shows that significant efficacy was obtained for a much broader group of children than had been included in the initial laboratory studies. Further analysis showed that differences in the degree of efficacy were *not* based on the child's clinical diagnostic classification, age, gender, or degree of impairment. That is, this intervention method was shown to improve language skills in both male and female children between the ages of 4 and 14 years with a variety of clinical diagnoses and across a broad range of language functioning. 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. Thus, this first multisite, field trial, which was conducted entirely by professional licensed SLPs in their own clinics or classrooms, showed that the results that we initially found in our controlled laboratory studies were broadly replicable in clinics and classrooms.

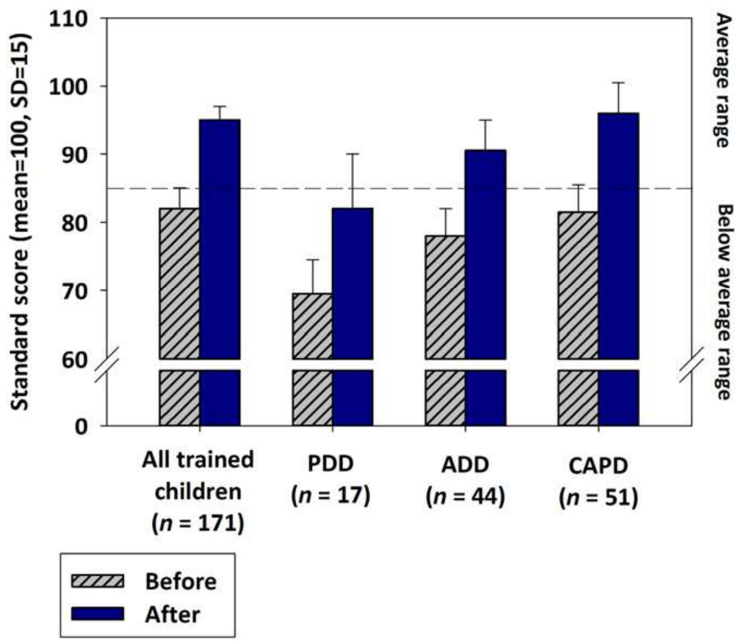

FIGURE 2

Comprehensive language quotients (Test of Language Development and Comprehensive Evaluation of Language Function) for all children pre- and post-Fast ForWord® training. Scores are shown for all children with language impairment (LI) combined, as well as for LI children diagnosed clinically as having pervasive developmental disorder (PDD), or with comorbid attention deficit disorder (ADD), or central auditory processing disorder (CAPD). Although the degree of language deficit differed at pretest among these groups of children (with children diagnosed as PDD having the most severe language disorder and CAPD having the least severe), there were no significant differences in the magnitude of improvement across groups achieved with training. All groups were 1 or more SD below the mean at pretest and showed significant improvement ($p < 0.0001$) from pre- to posttraining. Although the PDD group improved significantly following training, they still remained more than 1 SD below the mean following training, based on these test batteries. The children with LIs comorbid for ADD or CAPD entered the study with pretest scores more than 1 SD below the mean, while their average test scores approached the normal median posttraining.

Adapted from Tallal et al. (1998).

7.2 Second Field Trial: School-Based Randomized Control Trial (1997)

The second field trial was conducted in collaboration with 19 schools in 9 districts in California, Texas, Illinois, Indiana, and Nebraska. While the first field trial was focused on children receiving speech and language services in clinics and special schools, the purpose of the second field trial was to evaluate the effectiveness of *Fast ForWord® Language* in typical public schools. This randomized controlled trial included over 400 kindergarten through 3rd grades who were selected by their teachers as "at-risk" for academic failure. Once students were selected by their teachers as being "at risk," they were randomly assigned to either receive *Fast ForWord® Language* training or to receive the traditional educational services being provided in their school for "at-risk" students. Students in the Comparison group were matched by age and gender to the Experimental group. All participants also received a battery of standardized tests both at the beginning and end of the study.

One of the most striking findings from this field trial of school children selected by their classroom teacher as being "academically at risk" was the finding that, based on standardized test scores obtained prior to training, low *receptive language comprehension* test scores proved to be these children's most common problem. Recall that these teachers were *not* instructed or encouraged to select children for this trial based on language impairment, but rather based on their intuition that a child was "at risk for academic failure." As part of this study, we asked teachers to complete a checklist indicating why they thought the child was "at risk." Most frequently checked were reading problems, attention deficits, immaturity, and behavioral problems. Least frequently checked were language comprehension deficits. This suggests that classroom teachers are not aware that it may be weak receptive language skills that they are actually recognizing in "academically at risk" students. Rather, once a child begins to fail in formal education, it is assumed they are having difficulty learning to read and any special services they receive generally focus on improving reading and other literacy skills. This is compatible with results from an epidemiological study showing that only 29% of children meeting the criteria for SLI in kindergarten had ever been previously identified as language impaired (Tomblin, et al., 1997).

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. As presented in Fig. 3, after *Fast ForWord® Language,* post-training results showed that the oral language comprehension performance of these "academically at risk" children significantly improved, shifting substantially to within the normal distribution. These data confirmed the earlier findings from our laboratory-based control trial (Tallal et al., 1996). Consistent with the laboratory results, average gains in this school-based randomized trial were 1–2 years on standardized measures of language comprehension or phoneme awareness following 4–6 weeks of *Fast ForWord® Language* participation. Furthermore, improvements were significantly greater in children receiving *Fast ForWord® Language*, as compared to the control group receiving standard intervention strategies (see Miller et al., 1999; Tallal et al., 1998 for details).

Much of the data from these large-scale field trials have been published in book chapters rather than peer-reviewed journals (Merzenich et al., 1998,1999; Miller et al., 1999; Tallal et al., 1999). When we attempted to submit these data for publication in peer-reviewed academic journals, we encounter a surprising

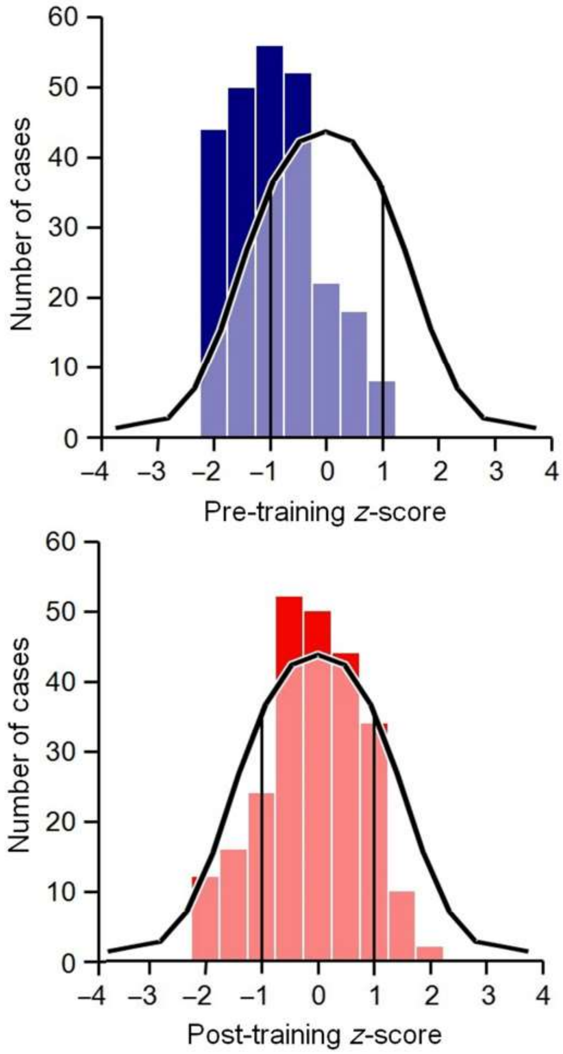

FIGURE 3

Pre- and post-Fast ForWord® Language v1 training frequency histograms for "at-risk" students using *z*-scores of language comprehension performance (TACL-R) for the speech and language training group (N-288). The bold lines superimpose a bell curve on the histogram to represent the standard normal distribution of scores on this test. The change from pre training (top) to posttraining (bottom) indicates a large positive shift in the distribution of performance following 4–8 weeks of training. Prior to training, the language comprehension performance for both groups was well-below average, approximately at the 12.5 percentile for the normal distribution (−1.14 *z*-scores), a finding consistent with the "at-risk" status assigned by their classroom teachers. At posttesting, control group performance (not shown) had improved (21st percentile or −0.8 *z*-scores), but was still well-below age-expected performance levels and lower than the performance of the training group (38th percentile or −0.3 *z*-scores). The number of subjects performing at or above the median in age-corrected language comprehension performance improved for the trained subjects from 11.4% to 39.0% as compared to 12.0% to 16.2% for the control group ($\chi 2 = 22.06$, $p < 0.0001$) for posttesting difference between experimental and control subjects. Scientific Learning Corporation MAPS for Learning: Product Report 3 (1)1:13. http://www.scilearn.com/alldocs/rsrch/sbr/30052ffwlanguageprodrpt.pdf.

setback to our translational efforts as scientists. Our papers were rejected, in some cases even from being considered for peer-review because they now pertained to a commercial product that we were helping to develop. When we raised the issue as to how research data being translated out of the lab into clinics and classrooms were supposed to be disseminated throughout the translational process, we were told by one journal editor that this kind of data generally was published in product manuals and on company websites, not in scientific journals.

7.3 *Fast ForWord® Language version 1 (v1)*: University-Based Studies

After our first studies were published in *Science*, there was a flurry of university-based studies that followed. Most of these studies focused on investigating the effectiveness of *Fast ForWord® Language v1* for children with SLI or dyslexia using behavioral, electrophysiological, and/or neuroimaging outcome measures.

7.3.1 Studies Using Behavioral Outcome Measures Only

Several of the early attempts to study *Fast ForWord® Language v1* were, unfortunately, premature as they were conducted soon after this first product was released and the software as well as the protocol for implementing it effectively in school settings was still undergoing substantial improvement. Also, because the results of the field trials had not been published in peer-reviewed journal, researchers could not take advantage of how these programs were evolving and how to implement them with fidelity. To the contrary, many researchers indicated that they explicitly wanted to evaluate the efficacy of *Fast ForWord® Language v1* as stand-alone software, without any input from SLC. However, *Fast ForWord®* products were designed as "blended" approaches that require ongoing interaction between a child and their professional provider. They were not designed to be used in the way they were implemented in many of the university-based studies that ended up getting published in peer-reviewed academic journals. As a result, many of these early studies suffered from very poor or nonstandard implementations. Five of these early studies constitute the only data used in an influential meta-analysis published by Strong et al. (2011). Unfortunately, there were many flaws in this publication. These authors adopted an unusually stringent set of criteria for accepting a study into their meta-analysis; only randomized control trials that included equivalent groups at study onset and had been published in a peer-reviewed academic journal were considered. Of the over 200 studies on *Fast ForWord® Language* that Strong et al. reviewed, only six studies met their strict criteria and one was dropped for lack of available data. It should be pointed out that several studies published in excellent peer-reviewed scientific journals, that had positive results, were excluded for unconventional reasons. Of the five studies that made the cut for this meta-analysis, three acknowledged having very poor compliance; one stated that nearly 40% of the posttest outcome data were either missing or unreliable. Another study used parents rather than the trained professionals to deliver the program to their own impaired child at home. It is also important to emphasize that regardless of when the study was actually published, all of the data included in this meta-analysis were collected prior to 2005 using two very early, and now discontinued, versions of *Fast ForWord® Language v1*.

Of the five studies included in the Strong et al. (2011) meta-analysis, the Gillam et al. (2008) NIH-funded trial had by far the best implementation. The results from this study demonstrated that students who used the *Fast ForWord® Language* products for 50 h achieved statistically significant improvements in language and reading skills—improvements comparable to an active control group receiving 50 h of one-on-one therapy with a licensed SLP. In this trial, 74% of the language impaired children who received *Fast ForWord® Langu*age had follow-up scores that were significantly higher than their pretest scores 6 months after treatment ended. In addition, those children who received the computer-based interventions significantly outperformed the active control groups in early reading skills, specifically phonological awareness. It is confounding, considering these positive data on the efficacy of *Fast ForWord® Language* reported in this NIH-funded trial, which is clearly the best of the five studies included in this meta-analysis, that Strong et al. (2011) published the following conclusion: "There is no evidence from the analysis carried out that Fast ForWord is effective as a treatment for children's oral language or reading difficulties." This statement is blatantly incorrect and in direct conflict with the actual data.

In the years since these early studies were conducted, SLC has significantly altered and improved the *Fast ForWord®* software, created improved protocols, and provided better training and support to schools and clinics. In addition, nine new products including a series of six products explicitly designed for reading intervention have been released. It is important to emphasize that none of the data included in this meta-analysis was derived from any of the currently used *Fast ForWord®* products. We encourage scientists and educators to consider the entire corpus of more than 200 studies on *Fast ForWord®* products that are available or summarized on the Scientific Learning website (http://www.scientificlearning.com/results). These studies demonstrate the efficacy that has been achieved using more current versions of *Fast ForWord® Language* (*v2 and Literacy*) and the *Reading* series (*Readiness and Levels 1–5*), as well as the benefits that accrue when these products are implemented with fidelity by experienced *Fast ForWord®* professionals in the educational and clinical settings for which they were designed.

7.3.2 Neurophysiological and Neuroimaging Studies of Fast ForWord® Language

Several laboratory studies on *Fast ForWord® Language* included physiological outcome measures. The first of these studies was conducted at Stanford University in John Gabrieli's lab in collaboration with a school that specialized in educating children diagnosed with developmental dyslexia (Temple et al., 2003). Children in this study received *Fast ForWord® Language* training in their school under the supervision of an experienced *Fast ForWord®* provider. Functional MRI was performed on 20 children with dyslexia (8–12 years old), while they performed a phonological processing task in the scanner, both before and after remediation with *Fast ForWord® Language*. Results showed significantly improved oral language and reading performance after training. After training, the children with dyslexia also showed increased metabolic activity in the left temporoparietal cortex and left inferior frontal gyrus, brain regions associated with phonological processing, bringing brain activation in these regions closer to that seen in typical readers. Increased activity was also observed in right-hemisphere frontal and temporal regions and in the anterior cingulate gyrus. Finally, a significant correlation was found between the magnitude of increased activation in left temporoparietal cortex and improvement in oral language ability.

In Gaab et al. (2007), whole brain fMRI was performed on 22 children with developmental dyslexia and 23 typical-reading children. In this study, nonspeech analogue stimuli that differed in the duration of onset and offset were used as stimuli. As had been found in adults, fMRI results with these nonspeech stimuli demonstrated that the typical-reading children showed activation for rapid (20 ms) compared to slow (200 ms) transitions in *left* prefrontal cortex. Children with developmental dyslexia failed to show any differential metabolic response in these regions to rapid versus slow transitions. Remarkably, after only 8 weeks of training with *Fast ForWord® Language*, the children with developmental dyslexia not only showed significant improvements in language and reading skills but also exhibited substantially "normalized" activation for rapid relative to slow transitions in left prefrontal cortex. Gaab et al. (2007) concluded that the presence of a disruption in the neural response to rapid versus slow acoustic transitions in children with developmental dyslexia prior to remediation, coupled with significant improvement in language and reading scores and increased brain activation after remediation, gives further support to the inclusion of training aimed at increasing RAP in interventions for reading disabilities.

A study done in Helen Neville's lab examined whether 6 weeks of high-intensity (100 min/day 5 days per week) training with *Fast ForWord® Language* would influence neural mechanisms of selective auditory attention previously shown to be deficient in children with SLI (Stevens et al., 2008). Twenty children, 8 diagnosed with SLI and 12 with typically developing language received training in the lab. An additional 13 children with typically developing language received no specialized training (NoTx control group) but were tested and retested after a comparable time period to control for maturational and test–retest effects. Before and after training, children completed standardized language assessments and an event-related brain potential measure of selective auditory attention. Relative to the NoTx control group, both the dyslexic and typical children who received training showed significant increases in standardized measures of receptive language as well as larger increases in the effects of attention on neural processing. The enhanced effect of attention on neural processing represented a large effect size (Cohen's $d = 0.8$) and was specific to changes in signal enhancement of attended stimuli. These findings indicate that the neural mechanisms of selective auditory attention, previously shown to be deficient in children with SLI, can be remediated through training and can accompany improvements on standardized measures of language. This was also the first study to show that significant enhancement of language and attention could be achieved after *Fast ForWord® Language* training not only in children with language impairments but also in typically developing children. That is, this form of training generalized to enhancing language skills in typical as well as impaired children.

In a recent study, Heim et al. (2011) used combined source modeling and time-frequency analysis of the human electroencephalogram (EEG) to examine the effects of *Fast ForWord® Language* training on early oscillatory responses in auditory cortex. Twenty-one elementary school students diagnosed with LLI received this training for an average of 32 days in a clinical setting under the supervision of an SLP experienced in delivering this program. Pre- and post-training assessments performed in the laboratory included standardized language/literacy tests and EEG recordings in response to fast-rate tone doublets. Twelve children with typical language development were tested and retested after a comparable time period to control for maturational and test–retest effects. As had been found in other studies using *Fast ForWord® Language* training, the LLI children made significant gains in receptive language skills post-training. Furthermore, during the first EEG assessment (pre-training), LLI children showed reduced amplitude and phase locking of early (45–75 ms) oscillations in the gamma-band range (29–52 Hz) for the second stimulus of the tone doublet. After *Fast ForWord® Language* training, amplitude reduction for the second tone in the sequence was no longer evident for the LLI children, although these children still exhibited attenuated phase locking.

Russo et al. (2010) also reported physiological improvements in auditory function in a study with children with autism spectrum disorders (ASD). Children with ASD share many common deficits to children diagnosed with SLI, including receptive language and auditory processing deficits. While these children have been included in field studies previously, and shown to benefit from *Fast ForWord® Language* training (see Fig. 2), this is the first laboratory-based study to address whether the language impairments that characterize children with ASD may potentially be alleviated through training-induced improvements in auditory processing. To assess the impact of *Fast ForWord® Language* training on auditory function in children with ASD, brainstem and cortical responses to speech sounds presented in quiet and noise were recorded from five children with ASD. These children received training by their clinician who had extensive experience providing *Fast ForWord® Language* to children with ASD. The results showed that relative to six control children with ASD, who did not receive *Fast ForWord® Language*, post-training-related changes were found in brainstem response timing in three of the five children with ASD, while pitch-tracking was found in only one ASD child. Impressively, all five of the trained children with ASD showed improvement in cortical response timing after *Fast ForWord® Language* intervention.

8 THE *FAST FORWORD®* *READING* SERIES

While the *Fast ForWord®* *Language* series was inspired by laboratory-based scientific research, which was then translated and scaled for use in clinics and classrooms, the *Fast ForWord®* *Reading* series was inspired by educators' need to improve the literacy skills of their students. Despite an increasing understanding by educators of the essential role of phonological awareness in early reading development, and despite the research showing the essential role of aural language development as the foundation on which proficient reading depends (Hart and Risley, 1995; Tallal, 1980), it soon became clear that the majority of educators were not particularly motivated to improve language proficiency in their students. The No Child Left Behind Act of 2001 (P.L.107–110 (H.R.1) Title I) gave educators a clear mandate—increase reading proficiency, as measured by statewide, "high stakes" achievement tests. In turn, educators gave SLC a mandate—make research informed products that will help us achieve this goals. The *Fast ForWord®* *Language* games focused on improving auditory processing, phonological processing, and language comprehension skills. There were *no letters* in any of these games. It soon became clear that if we wanted to make products that schools would use, they had better have letters in them!

Informed by decades of research on reading development (Mann, 2002, 2003) and with the help of some leading reading research scientists, SLC began to expand the original *Fast ForWord®* *Language* programs into a series of *Fast ForWord®* *Reading* programs. These programs moved systematically through the language to literacy continuum, and from reading readiness to middle and high school level reading. The *Fast ForWord®* *Reading* series is an intensive, computer-based series of six different programs that rapidly and systematically build reading skills from the ground up, while individually adapting to each student's ability level and knowledge base. *Fast ForWord®* *Reading* was designed to intensively train fundamental cognitive skills (including working memory, focused and sustained attention, and sequencing) while simultaneously building reading decoding, spelling, sentence comprehension, and passage comprehension. Each skill involves a number of other skills, such as phoneme awareness, sensitivity to letter-sound correspondences, understanding of morphological word changes, and knowledge of Standard American English grammar. Unlike the *Fast ForWord®* *Language* programs, which were originally designed for children with language-learning impairments, the *Fast ForWord®* *Reading* series is designed for any student who is working on learning to read and becoming a better reader, at any level from K-12th grade. The reading series does *not* use acoustically modified speech. It does, however, adhere to the same "scientific learning principals," as well as focus on training basic cognitive and linguistic skills, that underlie the *Fast For Word®* *Language* series. The major scientific advisors involved with developing the *Fast ForWord®* *Reading* series were Drs Virginia Mann, Steve Miller, and William Jenkins. These scientists worked from the onset in close collaboration with a dedicated team of educators, computer game designers, programmers, artists, animators, and writers at SLC over many years to develop the *Fast ForWord®* *Reading* series.

The *Fast ForWord® Reading* series currently includes the following six products; each product includes five to seven exercises "disguised" as computer games:

Fast ForWord® Reading Readiness builds prereading skills, with a focus on letter recognition and naming, phonological awareness, and letter-sound associations.
Fast ForWord® Reading Level 1 builds critical early reading skills, with an emphasis on phonemic awareness, early decoding skills, vocabulary knowledge and skills, and motivation for reading.
Fast ForWord® Reading Level 2 consolidates early reading skills, with a focus on applying phonics and decoding strategies, improving word recognition, and understanding the rules for reading comprehension.
Fast ForWord® Reading Level 3 builds on the *Fast ForWord® Reading* Level 2 product by concentrating on reading knowledge and fluency, with a focus on phonology and spelling, morphological properties and complexity, syntactic complexity, vocabulary and comprehension.
Fast ForWord® Reading Level 4 builds reading skills in school by applying knowledge of word origins, word forms, sentence structures, and punctuation rules to improve comprehension.
Fast ForWord® Reading Level 5 is appropriate for students in upper elementary, middle, and high school. It concentrates on enhancing advanced reading comprehension skills and expanding vocabulary skills.

Details pertaining to the science behind the development of each exercise within the *Fast ForWord® Reading* series, school-based research studies evaluating their efficacy, and descriptions and screen shots of each exercise can be found at: http://www.scilearn.com/products/fast-forword-reading-series/.

8.1 Independent School-Based Studies of the *Fast ForWord® Language and Reading* Series

Whereas *Fast ForWord® Language* grew out of laboratory-based basic research that was initially designed to address theoretical and experimental questions pertaining to the causes and determinants underlying individual differences in language development and disorders, and subsequently translated into products that could be used in clinics and classrooms, *Fast ForWord® Reading* products were developed based on *educators*' expressed need for more effective and efficient products for improving the literacy proficiency of their students. As such, the vast majority of research on *Fast ForWord® Reading* products comes from school-based studies initiated and conducted by educators trained to provide *Fast ForWord®* products within their own schools. Several research designs have been used in the assessment of efficacy of the *Fast ForWord® Reading* series. Many of the schools primarily wanted to see if they could get reading improvements in their struggling readers who, despite more traditional interventions, were continuing to fail to meet proficiency standards for their age and grade. Other studies used a repeated measures design that was based on tracking literacy scores on statewide standardized achievement tests over a number of years before and subsequently after the school introduced *Fast ForWord*® products. The goal of this design was to determine if the slope of the trajectory of students' scores was significantly increased after *Fast ForWord*® use. Figure 4 shows the highly significant results one district achieved using this design, both in literacy and math. Although it is very difficult to do in a regular school setting, some school-based studies conducted randomized control trials (RTC). Two were conducted by teachers in their own schools for their doctoral research (Rogowsky, 2010; Slattery, 2003). Both of these studies found significantly greater literacy improvements in the students who had been randomly assigned to receive *Fast ForWord*® training as compared to the students in the control groups who participated in another school program. For example, for her thesis research, Rogowsky (2010) conducted an RTC of *Fast ForWord® Literacy* and *Fast ForWord® Reading Level 2* products with middle school students. As a middle school writing instructor, she was particularly interested in whether these products would lead to improvements in Standardized Edited American English (SEAE) writing skills, as measured by a standardized writing assessment. After 6 weeks of training, her results showed that the children who had received *Fast ForWord*® training improved in authentic writing skills significantly more than those that had been randomly assigned to the active control groups. Rogowsky et al. (2013) followed up this middle school study with a college population. Twenty-five college students (12 native English language; 13 English Second Language), who demonstrated poor writing skills, received daily training during the spring semester (11 weeks) with *Fast ForWord® Literacy* and upper levels of *Fast ForWord® Reading* (Levels 3–5). A comparison groups of students ($N = 28$) attending the same university did not receive training. All students took the Gates MacGinitie Reading Test (GMRT) and the Oral and Written Language Scales (OWLS) at the beginning (Time 1) and end (Time 2) of the spring college semester. Results from this study showed that the training group made a statistically greater improvement from Time 1 to Time 2 in both their reading skills and their writing skills than the comparison group. As can be seen in Fig. 5, the group who received training began with statistically lower writing skills before training, but exceeded the writing skills of the comparison group after training (Rogowsky et al., 2013).

Studies on the effectiveness of educational interventions are inherently difficult, in part because of the many skill sets required to conduct these studies in real-world clinics and school settings. Before introducing a new method, curriculum, or product, schools have to answer a practical question: does the new approach lead to better outcomes for their students than whatever intervention strategies they currently have in place? In translating research from the laboratory to classrooms, we have found that most schools' administrators and curriculum directors are only willing to make important decisions for their school after they have conducted their own, internal, independent study. As a result, hundreds of independent school-based studies, some of them RTC, of one or more

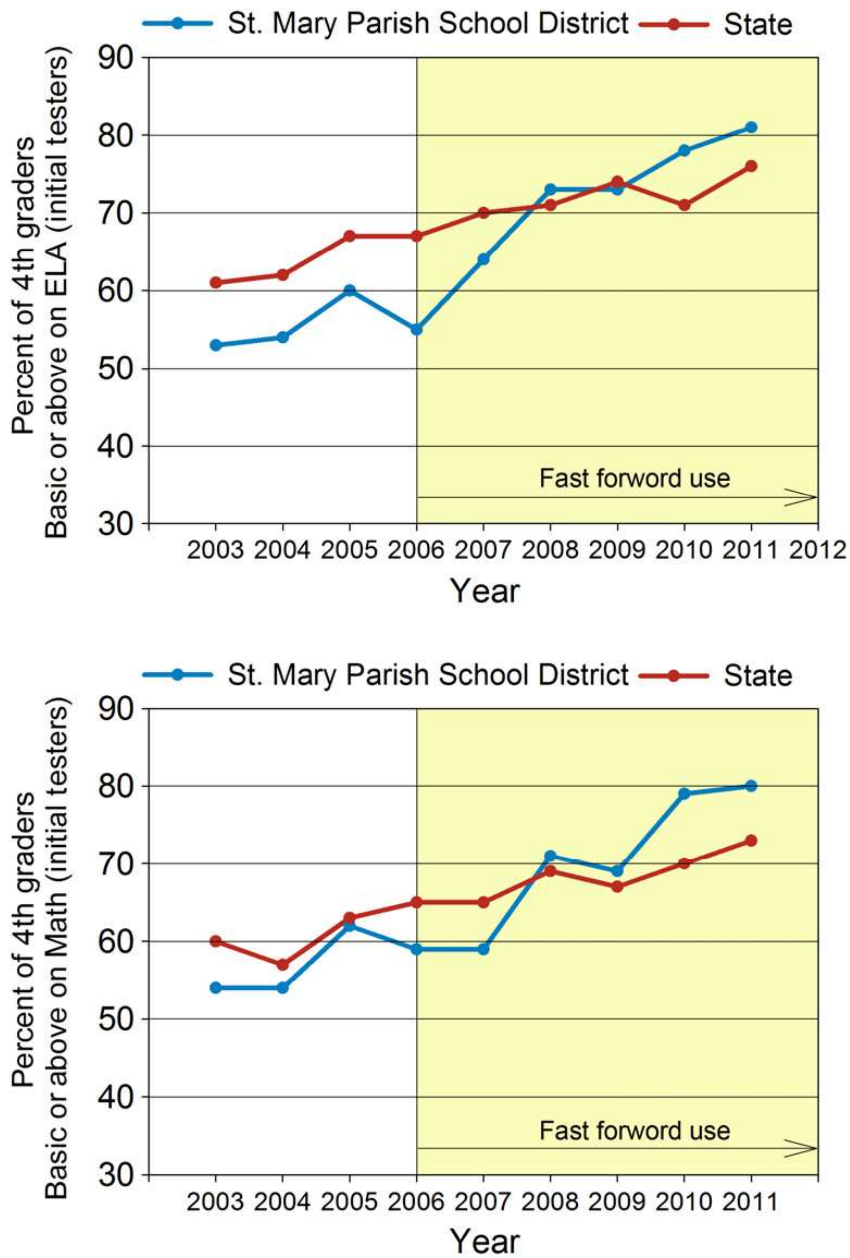

FIGURE 4

District-wide longitudinal trends of 4th-grade Louisiana Education Assessment Program (LEAP) achievement levels of the St. Mary Parish district in 2003 (3 years before Fast ForWord® implementation began in 2006) and extending through 2011, as compared to Louisiana state-wide LEAP scores. In the 2006–2007 school year, the St. Mary Parish Public School System started school-wide use of the Fast ForWord® Language and Reading products at eight elementary schools that were in Academic Assistance (a designation for schools that fail to improve sufficiently). During the 2008–2009 school year, the remaining elementary schools began using the Fast ForWord® products as well. Top: Percentage of students at or above Basic Level on initial LEAP English Language Arts (ELA). Bottom: Percentage of students at or above Basic Level on initial LEAP Math. Solid line: St. Mary's Parish School district, dashed line: state-wide average from 2006 to 2011, 4th grade English Language Arts proficiency levels rose from 55% to 81%; Math proficiency levels rose from 59% to 80%. Learning: Research Reports 16(2): 1–9. http://www.scilearn.com/alldocs/rsrch/sbr/30530stmaryparishedurpt.pdf.

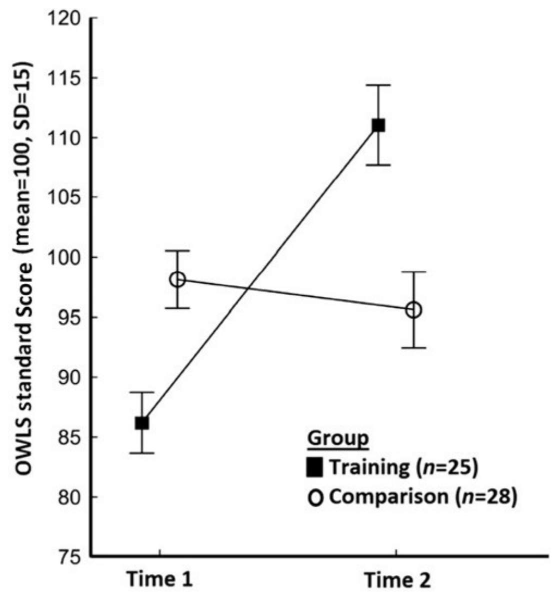

FIGURE 5

College students' Written Expression Scale standard scores of the Oral and Written Language Scales (OWLS) for struggling and average writers. Mean values for the struggling writers ($N = 25$) who participated in the training group (filled squares) and $N = 28$ comparison participants (open circles) are shown at Time 1 compared to Time 2, 11 weeks later. Vertical bars indicate standard errors of mean. While the comparison group outperformed the training group students on the OWLS Writing Expression Scale at Time 1, the trained group's considerable spurt in writing following Fast ForWord® Language v2 and Reading (Levels 3–5) intervention led to a reversed performance pattern at Time 2, with higher standard writing scores achieved by the trained students. From Rogowsky et al. (2013).

levels of *Fast ForWord® Language* and/or *Reading*, have been conducted by educators in their own schools. Unfortunately, K-12 educators do not write up their results for publication or read peer-reviewed academic journals, while scientists are generally only willing to accept data that have been vetted and published in peer-reviewed academic journals. This makes it exceedingly difficult for research scientists interested in educational translation and K-12 educators interested in research to find ways to communicate their findings and ideas to each other. In an attempt to bridge this gap, several independent agencies such as the US Department of Education's Office of Special Education Programs (OSEP), the National Center on Response to Intervention (NCRTI), and The What Works Clearinghouse (WWC) have developed stringent metrics for evaluating both study designs and outcome data from education research studies, based on the quality of a study rather than whether or not it has been published in a peer-reviewed journal.

9 INDEPENDENT AGENCY EVALUATIONS OF *FAST FORWORD®* PRODUCTS

The National Center on Intensive Intervention (NCII) is funded by the US Department of Education and housed at the American Institutes for Research. As part of their mission to help educators implement data-based individualized instruction, NCII reviews studies on various educational interventions used with struggling students, and publishes their analyses. According to their website, the NCII reviews focus on the degree to which intervention studies meet the following criteria: *Participants*: at-risk students in Grades K-12; *Study design*: two group study, preferably with random assignment, comparable initial skills and demographics between the two groups, and no attrition bias; *Fidelity of implementation*: data showing the program was used as designed; *Study measures*: accurate (psychometrically reliable) and important (relevant to the program's instructional content). Targeted measures assess skills targeted by the intervention. Broader measures assess related aspects of competence. NCII reviews also report the effect size found in each study. The effect size quantifies the impact of the intervention by comparing the post-intervention skills of the two groups (a medium effect size is around 0.5, while a large effect size is around 0.8). NCII reviewed three studies on the *Fast ForWord® Language* products: (1) Miller et al. (1999). This RTC study included 388 students. Result demonstrated positive efficacy with a Medium (0.59) effect size; (2) Scientific Learning Corporation (2004). This study used a matched group design and included 50 students. Result demonstrated positive efficacy with a Medium (0.44) effect size; and (3) Slattery (2003). This RTC included 60 students. Result demonstrated highly positive improvements with a Large (1.44) effect size. For full report, see http://www.intensiveintervention.org/chart/instructional-intervention-tools.

Using funding from the US Department of Education's Office of Special Education Programs (OSEP), the National Center on Response to Intervention (NCRTI) was established by the American Institutes for Research and researchers from Vanderbilt University and the University of Kansas. According to their website, the Center provides guidance to educators on implementing proven models for Response to Intervention (RTI) and Early Intervening Services (EIS). NCRTI reviews studies evaluating the impact of various products on struggling students. The reviews focus on the following components of the study: *Participants*: students in 5th grade and below; students below the 30th percentile or groups that average below the 25th percentile; *Study design*: two group, preferably random assignment. Analysis showing comparable initial skills between the two groups, demographic breakdown showing similar demographics between the two groups; *Fidelity of implementation*: data showing the product was used as designed; *Study measures*: accurate and relevant (psychometrically valid). Proximal measures assess skills directly targeted by the intervention; distal measures assess aspects of competence that are related to the targeted skills. In addition to reporting on the four components of interest, NCRTI reports the effect size. NCRTI reviewed the same three studies on the *Fast ForWord® Language* products as cited above ($N=498$

students), breaking out results further into Proximal and Distal effect sizes. The two RCT studies (Miller et al., 1999; Slattery, 2003) showed large proximal effect sizes (7.45 and 1.46, respectively), while the Slattery study also showed a Large Distal effect size (1.05). For full report, see http://www.rti4success.org/instructionTools.

Nevada Senate Bill 185 (SB 185) funded districts to purchase and implement innovative and remedial educational programs, materials, and strategies specific to their academic needs. The Nevada Department of Education commissioned the Colorado-based Leadership and Learning Center (LLC) to conduct an in-depth evaluation of the programs that were purchased with SB 185 grants. Their 2010 Interim Report includes a review of the performance of *Fast ForWord®* products, which were used at three schools. The Leadership and Learning Center used multivariate analysis to determine the impact of programs on student achievement: "Emphasis was placed on measuring student growth toward academic proficiency and mastery using state and local assessments. . .. The analyses were completed as a result of extensive site visits, phone interviews, and an examination of two-year sets of school cohort achievement data for Criterion- Referenced Tests (CRT) for grades three through eight and High School Proficiency Exams (HSPE) for grades nine through twelve." The advantage of this report is that it compares many of the currently available commercial products. This report concludes that *Fast ForWord®* products increased student reading achievement scores by an average of 22.2 percentage points. *Fast ForWord®* was found to have the *largest average impact* of all programs reviewed in the report and it qualified *Fast ForWord®* to be classified as a "High-Gain Program."

The What Works Clearing House (WWC) was created by the NSF Institute for Education Sciences (IES) to review and give ratings to products and programs aimed at teaching and improving academic skills. According to their website the WWC has developed and standardized a stringent rating scale both for the quality of a research study as well as the effectiveness of a product or program. WWC selects specific topics of most concern to educators, strictly defines the scope for each topic area, and specifies the grade range that each review will include. *Fast ForWord®* products have been reviewed and received positive rating in three areas: Early Reading K-3rd grade, Adolescent Literacy 3rd–10th grade, and English Language Development K-6th grade.

WWC: Early Reading Effectiveness Rating K-3rd Grade. The WWC identified nine studies of *Fast ForWord®* that both fell within the scope of the Beginning Reading topic area and met WWC evidence standards. Seven studies met standards without reservations and two studies meet WWC evidence standards with reservations. Together, these studies included 1390 students from several areas of the United States and Western Australia. Results show that WWC considers the extent of evidence for *Fast ForWord®* on the reading skills of beginning readers to be medium to large for two outcome domains—alphabetics and comprehension—and small for one outcome domain—reading fluency.

WWC: Adolescent Literacy Effectiveness Rating Grades 3-10. The WWC identified two studies of *Fast ForWord®* that fell within the scope of the Adolescent Literacy review protocol that met evidence standards, and six studies that met WWC evidence standards with reservations. The eight studies included approximately 2000 students, ranging in age from 5 to 17 years, who attended elementary, middle, and high schools in Indiana, Maryland, North Carolina, Ohio, Pennsylvania, Virginia, an urban district in the northeastern United States, and Australia. Based on these eight studies, the WWC considered the extent of evidence for *Fast ForWord®* on adolescent learners to be small for the alphabetics and reading fluency domains and medium to large for the comprehension and general literacy achievement domains.

WWC: English Language Development Grades K-6. The WWC identified one study of *Fast ForWord® Language* that met evidence standards and a second study that met standards with reservations. The two studies included a total of 250 K—6th grade English Language Learners (ELL) from 16 school districts. The studies examined English language development and reading achievement. For some unspecified reason, for this topic area phonological and phoneme awareness, which are the most important early reading skills for elementary ELL and those that *Fast ForWord® Language* has been shown to most significantly improve, were considered to be outside the scope of this review and were not included in measures of reading achievement. Given that none of the *Fast ForWord® Reading* products were evaluated, improvement in higher levels of reading would not be expected. On the other hand, *Fast ForWord® Language* received a positive rating for improvement of English language development, raising the English language scores of ELL students by an average of +31 percentile points. This was one of the highest ratings given by WWC for English Language Development for ELL K-6 students.

10 COGNITIVE NEUROTHERAPEUTICS: THE CHALLENGES OF TRANSLATION

The biggest challenge we have faced along our journey to translate our laboratory research into real-world settings has been negotiating the torturous path between the world of scientists, as compared to the very different world of K-12 educators and clinicians who make the decisions about whether our products will be offered to the children who could benefit from them. Nowhere have these different worlds collided more directly than when it comes to assessing and reporting the efficacy of *Fast ForWord®* products. Our university-based colleagues have primarily used a combination of behavioral, physiological, and neuroimaging technologies to address questions about neuroplasticity-based training that have the potential to advance scientific knowledge and theory. Scientists are experts at designing elegant studies in which we can manipulate one variable at a time, within a well-controlled environment. These studies generally include "active control" methods designed to assess not only efficacy but also specificity. Many "active controls," designed for research purposes, are not scalable and would be prohibitively expensive to implement in a real-world settings. For example, the NIH-funded *Fast ForWord®* trial used 50 h of one-on-one therapy provided by a licensed SLP as an "active control" in order to match the 50-h training protocol for *Fast ForWord*® (Gillam et al., 2008). Finding that these two methods were highly successful in increasing language scores, albeit equivalent, was interpreted as a failure to demonstrate specificity for *Fast ForWord*®. However, providing the intensity of therapy used as the active control in this study to the majority of students who need it is cost prohibitive in the real world. What schools, clinics, and parents need to know is how a new method, like *Fast ForWord*®, compares to the actual alternatives that *are* available to their students, not hypothetical ones that are not. As such, these same results have an entirely different valence to educators, clinicians, and parents searching for cost-effective methods to serve their students and view them as strongly positive scientific evidence supporting their own experience using *Fast ForWord*®.

Regardless of whether research scientists studying the science of learning are involved directly in translating research from their lab to clinics and/or classrooms, most state in their grant applications that a primary goal of their research is to improve educational and/or clinical outcomes. However, the reality is that we face considerable challenges should we actually attempt to make good on this promise. The catch 22 is that many scientists are eager to translate our research ideas and innovations into practical, clinical, and educational applications. However, once these innovations are translated, they take on a life of their own to meet the needs of the intended end users. The reality is that most clinicians and K-12 educators neither read nor publish their work in peer-reviewed academic journals. Conversely, university-based scientists are either unaware of or have been reluctant to value data collected by educators and clinicians in school-based and/or clinical studies. Despite the best of intentions, scientists, clinicians, and educators continue to be akin to the proverbial ships passing in the night. The work being done by independent agencies such as the WWC, NCRTI, and NCII to bridge this gap is certainly a step in the right direction. However, if we as scientists are serious about translating our research into practical applications, which have the potential to change brains and enhance human potential, we need to develop more effective, *bidirectional* ways to collaborate, communicate, and learn from the consumers of our research and engage with them as equal partners throughout the ongoing, iterative, translational process.

References

Bates, E., Tomasello, M., 2001. Language Development: The Essential Readings. Wiley, NY.

Bedi, G., Miller, S., Merzenich, M., Jenkins, W.M., Tallal, P., 1999. Efficacy of neuroscience-based training for receptive language and auditory discrimination deficits in language-learning impaired children: a follow up study. Paper presented at the Cog. Neurosci. Soc., Washington.

Benasich, A.A., Tallal, P., 2002. Infant discrimination of rapid auditory cues predicts later language impairment. Behav. Brain Res. 136 (1), 31.

Chang, E.F., Merzenich, M.M., 2003. Environmental noise retards auditory cortical development. Science 300 (5618), 498–502.

Clopton, B.M., Winfield, J.A., Flammino, F.J., 1974. Tonotopic organization: review and analysis. Brain Res. 76, 1–20.

Curtiss, S., Yamada, J., 2013. The CYCLE ©, www.thecycletest.com.

Eggermont, J.J., 1981. Spectrotemporal characterization of auditory neurons: redundant or necessary? Hear. Res. 5, 109–121.

Gaab, N., Gabrieli, J.D.E., Deutsch, G.K., Tallal, P., Temple, E., 2007. Neural correlates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: an fMRI study. Restor. Neurol. Neurosci. 25 (3–4), 295–310.

Gillam, R.B., Frome, L.D., Hoffman, L.M., Bohman, T., Champlin, C.A., Thibodeau, L., Widen, J., Brandel, J., Friel-Patti, S., 2008. The efficacy of Fast ForWord Language intervention in school-age children with language impairment: a randomized controlled trial. J. Speech, Lang., Hear. Res. 51, 97–119.

Hart, B., Risley, T.R., 1995. Meaningful Differences in Everyday Experience in Young American Children. Brookes, Baltimore, MD.

Hebb, D.O., 1949. The Organization of Behavior: A Neuropsychological Theory. Wiley, NY.

Heim, S., Benasich, A.A., 2006. Disorders of language. In: Chicchetti, D., Cohen, D. (Eds.), Developmental Psychopathology, second ed. Wiley, New York, pp. 268–316.

Heim, S., Friedman, J.T., Keil, A., Benasich, A.A., 2011. Reduced sensory oscillatory activity during rapid auditory processing as a correlate of language-learning impairment. J. Neurolinguistics 24 (5), 539–555.

Hickok, G., Poeppel, D., 2007. The cortical organization of speech processing. Nat. Rev. Neurosci. 8 (5), 393–402.

Jenkins, W.M., Merzenich, M.M., Ochs, M.T., Allard, T., Guic, R.E., 1990. Functional reorganization of primary somatosensory cortex in adult owl monkeys after behaviorally controlled tactile stimulation. J. Neurophysiol. 63, 82–104.

Kraus, N., McGee, T., Carrell, T.D., Sharma, A., 1995. Neurophysiologic bases of speech discrimination. Ear Hear. 16, 19–37.

Kraus, N., McGee, T.J., Carrell, T.D., Zecker, S.G., Nicol, T.G., Koch, D.B., 1996. Auditory neurophysiologic responses and discrimination deficits in children with learning problems. Science 273, 971–973.

Kuhl, P.K., Andruski, J.E., Chistovich, I.A., Chistovich, L.A., Kozhevnikova, E.V., Ryskina, V.L., Stolyarova, E.I., Sundberg, U., Francisco, L., 1997. Cross-language analysis of phonetic units in language addressed to infants. Science 277 (1), 684–686.

Leonard, L.B., 1998. Children with Specific Language Impairment. MIT Press, Cambridge.

Liu, H.M., Kuhl, P.K., Tsao, F.M., 2003. An association between mothers' speech clarity and infants' speech discrimination skills. Dev. Sci. 6, 10.

Mann, V.A., 2002. Reading disorders, developmental. In: Ramachandran, V.S. (Ed.), The Encyclopedia of the Human Brain. Academic Press, San Diego, pp. 141–154.

Mann, V.A., 2003. Language processes: keys to reading disability. In: Swanson, H.L., Harris, K.R., Graham, S. (Eds.), Handbook of Learning Disabilities. Guilford Press, NY, pp. 213–228.

Merzenich, M.M., Jenkins, W.M., 1998. Cortical plasticity, learning, and learning dysfunction. In: Julesz, B., Kovacs, I. (Eds.), Maturational Windows and Adult Cortical Plasticity. Addison-Wesley, New York, NY, pp. 247–272.

Merzenich, M.M., Jenkins, W.M., Johnston, P., Schreiner, C., Miller, S.L., Tallal, P., 1996. Temporal processing deficits of language-learning impaired children ameliorated by training. Science 271 (5245), 77–81.

Merzenich, M.M., Tallal, P., Peterson, B., Miller, S.L., Jenkins, W.M., 1999. Some neurological principles relevant to the origins of—and the cortical plasticity based remediation of—language learning impairments. In: Grafman, J. (Ed.), Neuroplasticity: Building a Bridge from the Laboratory to the Clinic. Elsevier, Amsterdam, pp. 169–187.

Miller, S.L., Linn, N., Tallal, P., Merzenich, M.M., Jenkins, W.M., 1999. Acoustically modified speech and language training: a relationship between auditory word discrimination training and measures of language outcome. Speech and Language Therapy, 197, 159–182.

Nagarajan, S.S., Wang, X., Merzenich, M.M., Schreiner, C.E., Johnston, P., Jenkins, W.M., Miller, S., Tallal, P., 1998. Speech modifications algorithms used for training language learning-impaired children. IEEE Trans. Rehabil. Eng. 6, 257–268.

Neville, H.J., 1985. Effects of early sensory and language experience on the development of the human brain. In: Mehler, J., Fox, R. (Eds.), Neonate Cognition: Beyond the Blooming Buzzing Confusion. Lawrence Erlbaum, Hillsdale, NJ, pp. 349–363.

Orduna, I., Mercado, E., Guck, M.A., Merzenich, M.M., 2001. Spectrotemporal sensitivities in rat auditory cortical neurons. Hear. Res. 160, 47–57.

Recanzone, G.H., Schreiner, C.E., Merzenich, M.M., 1993. Plasticity in the frequency representation of primary auditory cortex following discrimination training in adult owl monkeys. J. Neurosci. 13, 87–104.

Rogowsky, B.A., 2010. The Impact of Fast ForWord (RTM) on Sixth Grade Students' Use of Standard Edited American English. Doctor of Education dissertation, Wilkes Univesity, Wilkes, PA.

Rogowsky, B.A., Papamichalis, P., Villa, L., Heim, S., Tallal, P., 2013. Neuroplasticity-based cognitive and linguistic skills training improves reading and writing skills in college students. Front Psychol. 4, 137.

Russo, N., Hornickel, J., Nicol, T., Zeckler, S., Kraus, N., 2010. Biological changes in auditory function following training in children with autism spectrum disorders. Behav. Brain Funct. 6, 60.

Saffran, J.R., Aslin, R.N., Newport, E.L., 1996. Statistical learning by 8-month-old infants. Science 274 (5294), 1926–1928.

Slattery, C.A., 2003. The Impact of a Computer-Based Training System on Strengthening Phonemic Awareness and Increasing Reading Ability Level. Doctor of Education dissertation, Widener University, Chester, PA.

Stark, R., Tallal, P., 1988. Language, Speech and Reading Disorders in Children: Neuropsychological Studies. College Hill Press, Boston MA.

Stevens, C., Fanning, J., Coch, D., Sanders, L., Neville, H., 2008. Neural mechanisms of selective auditory attention are enhanced by computerized training: electrophysiological evidence from language-impaired and typically developing children. Brain Res. 1205, 55–69.

Strong, G.K., Torgerson, C.J., Torgerson, D., Hulme, C., 2011. A systematic meta-analytic review of evidence for the effectiveness of the 'Fast ForWord' languge intervention program. J. Child Psychol. Psychiatry 52 (3), 224–235.

Tallal, P., 1980. Auditory temporal perception, phonics, and reading disabilities in children. Brain Lang. 9 (2), 182–198.

Tallal, P., 2004. Improving language and literacy is a matter of time. Nat. Rev. Neurosci. 5 (9), 721–728.

Tallal, P., Piercy, M., 1973. Defects of non-verbal auditory perception in children with developmental aphasia. Nature 241, 468–469.

Tallal, P., Piercy, M., 1974. Developmental aphasia: rate of auditory processing and selective impairment of consonant perception. Neuropsychologia 12 (1), 83–93.

Tallal, P., Piercy, M., 1975. Developmental aphasia: the perception of brief vowels and extended stop consonants. Neuropsychologia 13 (1), 69–74.

Tallal, P., Galaburda, A.M., Llinas, R.R., von Euler, C., 1993. Temporal Information Processing in the Nervous System: Special Reference to Dyslexia and Dysphasia. Annals New York Academy of Sciences, NY.

Tallal, P., Miller, S.L., Bedi, G., Byma, G., Wang, X., Nagarajan, S.S., Schreiner, C., Jenkins, W.M., Merzenich, M.M., 1996. Language comprehension in language-learning impaired children improved with acoustically modified speech. Science 271 (5245), 81–84.

Tallal, P., Merzenich, M., Miller, S., Jenking, W., 1998. Language learning impairments: integrating basic science, technology and remediation. Exp. Brain Res. 123, 210–219.

Tallal, P., Miller, S., Jenkins, W.M., Merzenich, M.M., 1999. Moving research from the laboratory to clinics and classrooms. In: Duane, D. (Ed.), Reading and Attention Disorders: Neurobiological Sources of Co-Morbidity. York Press, San Diego.

Temple, E., Deutsch, G.K., Poldrack, R.A., Miller, S.L., Tallal, P., Merzenich, M.M., Gabrieli, J.D.E., 2003. Neural deficits in children with dyslexia ameliorated by behavioral remediation: evidence from functional MRI. PNAS 100 (5), 2860–2865.

Todorov, E., 2006. Optimal control theory. In: Doya, K. (Ed.), Bayesian Brain. MIT Press, Cambridge.

Tomblin, J.B., Records, N.L., Buckwalter, P., Zhang, X., Smith, E., O'Brien, M., 1997. Prevalence of specific language impairment in kindergarten children. J. Speech Hear. Res. 40, 1245–1260.

Wang, X., Merzenich, M.M., Sameshima, K., Jenkins, W.M., 1995. Remodeling of hand representation in adult cortex determined by timing of tactile stimulation. Nature 378 (2), 71–75.

Zhang, L.I., Bao, S., Merzenich, M.M., 2001. Persistent and specific influences of early acoustic environments on primary auditory cortex. Nat. Neurosci. 4, 1123–1130.

This page intentionally left blank