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Early gamma oscillations during rapid auditory processing in children with a language-learning impairment: Changes in neural mass activity after training

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ABSTRACT

Children with language-learning impairment (LLI) have consistently shown difficulty with tasks requiring precise, rapid auditory processing. Remediation based on neural plasticity assumes that the temporal precision of neural coding can be improved by intensive training protocols. Here, we examined the extent to which early oscillatory responses in auditory cortex change after audio-visual training, using combined source modeling and time-frequency analysis of the human electroencephalogram (EEG). Twenty-one elementary school students diagnosed with LLI underwent the intervention for an average of 32 days. Pre- and post-training assessments included standardized language/literacy tests and EEG recordings in response to fast-rate tone doublets. Twelve children with typical language development were also tested twice, with no intervention given. Behaviorally, improvements on measures of language were observed in the LLI group following completion of training. During the first EEG assessment, we found reduced amplitude and phase-locking of early (45–75 ms) oscillations in the gamma-band range (29–52 Hz), specifically in the LLI group, for the second stimulus of the tone doublet. Amplitude reduction for the second tone was no longer evident for the LLI children post-intervention, although these children still exhibited attenuated phase-locking. Our findings suggest that specific aspects of inefficient sensory cortical processing in LLI are ameliorated after training.

1. Introduction

The human cerebral cortex is a massively parallel, dynamic network, which is continuously reorganizing itself in a nonlinear fashion (Elbert & Heim, 2001). During ontogenesis, the development of this complex neuropil is impacted by a spectrum of factors ranging from genetic to experience-related influences (Gilbert, Dobyns, & Lahn, 2005; Penhune, 2011). Variations in genes and environment may result in conditions, which negatively diverge from typical brain and behavioral development. In this vein, language-based learning disabilities, including specific language impairment (SLI; problems in oral language acquisition) and dyslexia (difficulty in learning to read and spell) have been hypothesized to be a consequence of atypical cortical organization (Merzenich, Schreiner, Jenkins, & Wang, 1993). Given the neurobehavioral similarities between SLI and dyslexia, the term language-learning impairment (LLI) has become increasingly popular among researchers to encompass children with language and/or literacy difficulties (Tallal, 2001). Children with LLI have frequently been found to exhibit deficiencies in perceiving rapid changes in acoustic signals. This deficit may hinder the acquisition of precise phonemic temporal structures, during sensitive periods of development (Tallal, 2004). Phonemic representations are thought to contribute to higher-level linguistic learning, from semantics (word meaning) to syntax (grammatical rules), and ultimately for linking graphemes (printed characters) to phonemes (smallest meaningful sounds; Pennington & Bishop, 2009; Peeva et al., 2010). Accordingly, a set of prospective longitudinal studies using convergent methods have emphasized the essential role of rapid auditory processing (RAP) skills in infancy for later language achievement (Heim & Benasich, 2006; Choudhury & Benasich, 2011). Research on experience-related changes of sensory cortical maps in animals (de Villers-Sidani & Merzenich, 2011) has supported the notion that dysfunctional phonemic representations may be altered beyond early childhood. This approach has led to the design of neuroplasticity-based remedies, which assume that the temporal precision of neural coding can be enhanced by intense training in an optimal learning environment.

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Fast ForWord Language® (FFW) is a computerized intervention program with the focus to establish RAP skills underlying oral language and early reading abilities (Scientific Learning Corporation, 2001). Children with LLI who completed FFW in controlled learning settings exhibited not only an acceleration in auditory rate processing, but also significant gains on measures of language and literacy, as well as complimentary changes in metabolic brain activity (Merzenich et al., 1996; Tallal et al., 1996; Temple et al., 2003; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007).

The present research examined the extent to which FFW intervention is related to changes in the temporal organization of sensory processing in LLI. A sensory brain response that is well-suited to study temporal organization is the evoked gamma-band response (GBR), which can be readily extracted from the electroencephalogram (EEG). Evoked GBRs in sensory systems have been associated with re-tuning of cortical networks underlying perception as a function of emotional learning (Heim & Keil, 2006; Keil, Stolarova, Moratti, & Ray, 2007). Of interest for the present study, evoked GBRs have also been implicated as a potential index of matching processes comparing incoming stimulus features with existing memory representations (Herrmann, Munk, & Engel, 2004). Auditory GBRs are quantified by time-frequency analysis of EEG segments recorded while listening to auditory events (Pantev, 1995). Typically characterized by an early onset (50–70 ms post-stimulus) and a frequency of around 40 Hz, these phase-locked oscillations have been linked to integrative processing and plastic changes in sensory networks (Knief, Schulte, Bertrand, & Pantev, 2000). Because GBRs are defined in the frequency domain, phase-locking indices can be computed in addition to amplitude measures, describing the temporal stability of oscillatory activity across trials (Lachaux, Chavez, & Lutz, 2003).

Previous work has demonstrated the sensitivity of early GBRs to inter-individual differences in RAP: Adults with poor reading abilities have been reported to show attenuated cross-scalp coherence in the gamma range (a measure of spectral similarity across electrodes) to brief and rapid successive tones, compared to adults with average reading performance (Nagarajan et al., 1999). With respect to the condition LLI, Heim, Friedman, Keil, and Benasich (2011) found that diagnosed school-age children exhibited lower gamma power and phase synchronization to the second of two fast-rate complex tones than their typically developing peers. The goal of the present study was to explore whether the atypical GBRs to rapid acoustic signals in LLI change after an intervention protocol tapping into RAP skills. Because we were interested in sequence processing, crucial for language decoding, we used a paradigm presenting stimuli in rapidly sequential pairs, focusing our analysis on the second tone of the pair. Brain responses to the second stimulus of a doublet are often considered a reflection of temporally extended effects exerted by the first stimulus. Thus stimulus-pair relations are frequently examined in studies of sensory gating (Müller, Keil, Kissler, & Gruber, 2001), or rapid serial presentation (Keil & Heim, 2009). In the present study, we hypothesized that training with FFW under the guidance of a certified provider is accompanied by relative enhancement of GBR amplitude and phase-locking evoked by the second tone in the pair. Consistent with the perspective that RAP skills contribute to successful language acquisition, and discrepancies in RAP have been linked to LLI (Heim & Benasich, 2006; Tallal & Gaab, 2006), improvements in standardized measures of oral and written language were predicted as well. Little or no variation across a time interval comparable to FFW implementation was expected to occur in the non-treatment group of children with typical language development (TLD). Although the present study design does not permit drawing conclusions in terms of causal contributions of a specific treatment, adding this group allowed us to evaluate effects not related to the intervention, such as short-term maturational/developmental changes or the consequences of retesting on oscillatory brain activity and behavioral performance.

2. Methods

2.1. Study participants

Children who were tested in our previous study, exploring early auditory oscillatory responses to fast-rate stimulus sequences (Heim et al., 2011), were invited to participate in the current research. The LLI group ($n=29$) had the opportunity to receive FFW intervention, which was followed upon completion by a second assessment period at the laboratory. Four children and their parents decided not to attend the program, three discontinued FFW, and one child did not complete post-testing. Of the 18 children with TLD, six were not available for further behavioral and EEG assessment. Accordingly, a total of 33 children with English as the primary language constituted the present study sample. During the children's first visit to the laboratory, they were 6–9 years old with an average age of 8.11 years. Twelve participants (six girls) with TLD comprised the control group and 21 participants (six girls), formally diagnosed as language impaired, the LLI group. The LLI children were ascertained from private speech and language services in the metropolitan New York area and throughout New Jersey. Participants had to meet the following LLI criteria:

(1) Language skills assessment based on administered standardized measures: (a) Overall standard core language score or at least two overall standard language index scores (receptive language, expressive language, language content, language structure) of the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003) less than or equal to 85 (≥ 1 standard deviation [SD] below the mean of 100); or (b) at least three standard subtest scores of the CELF-4 less than or equal to 8 ($\leq$25th percentile) with a history of language therapy or intervention within the last 6 months; or (c) criteria #b plus standard reading scores of three Woodcock Reading Mastery Tests–Revised (WRMT-R; Woodcock, 1987), namely word identification, word attack, and passage comprehension less than or equal to 85.
Criteria ♯1b and ♯1c allowed children into the study having significant disparities in various language functions, with very low performance in some skills and average performance in others. Using overall language scores (CELF-4 core or index scores) alone would obscure such weaknesses because multiple subtests are used to generate composite scores and can "average out" to a standard score in the normal range.
(2) Nonverbal intelligence score as indicated by the performance IQ of the Wechsler Abbreviated Scale of Intelligence (WASI; The Psychological Corporation, 1999) of at least 85.
(3) Absence of hearing impairment, neurological disease, pervasive developmental disorder, dyspraxia, and psychiatric condition as determined by parental report.

Control participants with TLD were matched by chronological age (Table 1) and fulfilled criteria ♯2 and ♯3. Oral language skills had to fall within the normal range (standard score >85) as assessed by the CELF-4. In addition, the children must have had unremarkable pre- and perinatal circumstances, been born full-term and of normal birth weight, and have no known family history of LLI.

The TLD participants were recruited through local New Jersey schools. Children and siblings of children involved in a prospective longitudinal study at the Infancy Studies Laboratory at Rutgers University were invited to participate as well; these children were originally ascertained from pediatric practices in Northern New Jersey.

Basic demographic information is listed in Table 1, indicating that the LLI and TLD group did not significantly differ in terms of birth weight, gestational age, socioeconomic status, maternal age, and maternal education level. While all of the TLD participants reported right-hand dominance, there were two left-handed children and one ambidextrous child in the LLI group. Since handedness might have an influence on the interhemispheric configuration of the oscillatory brain response, the statistical analyses presented below were also carried out with a subsample that only included right-handed individuals. The observed effects in Section 3 were replicated, which prompted us to retain the non-right-handed LLI children in the study sample.

Table 2 shows that both groups satisfied inclusion criteria related to language and cognitive status. Consistent with their difficulties, LLI children had, on average, significantly lower scores in oral language (CELF-4) and reading (WRMT-R) measures than TLD children. All participants performed in the average or above-average age range on the WASI performance scale, with no significant group differences in nonverbal intellectual functioning. Paired samples t-tests between CELF-4 (core, receptive, and expressive) and WASI performance IQ variables revealed that the LLI children had lower language scores than would be expected