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Spectral vs. temporal auditory processing in specific language impairment: A developmental ERP study

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ABSTRACT

Pre-linguistic sensory deficits, especially in "temporal" processing, have been implicated in developmental language impairment (LI). However, recent evidence has been equivocal with data suggesting problems in the spectral domain. The present study examined event-related potential (ERP) measures of auditory sensory temporal and spectral processing, and their interaction, in typical children and those with LI (7–17 years; $n = 25$ per group). The stimuli were three CV syllables and three consonant-to-vowel transitions (spectral sweeps) isolated from the syllables. Each of these six stimuli appeared in three durations (transitions: 20, 50, and 80 ms; syllables: 120, 150, and 180 ms). Behaviorally, the group with LIs showed inferior syllable discrimination both with long and short stimuli. In ERPs, trends were observed in the group with LI for diminished long-latency negativities (the N2–N4 peaks) and a developmentally transient enhancement of the P2 peak. Some, but not all, ERP indices of spectral processing also showed trends to be diminished in the group with LI specifically in responses to syllables. Importantly, measures of the transition N2–N4 peaks correlated with expressive language abilities in the LI children. None of the group differences depended on stimulus duration. Therefore, sound brevity did not account for the diminished spectral resolution in these LI children. Rather, the results suggest a deficit in acoustic feature integration at higher levels of auditory sensory processing. The observed maturational trajectory suggests a non-linear developmental deviance rather than simple delay.

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1. Introduction

Language impairment (LI), a.k.a. specific language impairment (SLI), is a neuro-developmental disorder characterized by language deficits with relative sparing of other cognitive domains (Bishop, 1997; Leonard, 1997). In English-speaking children, language difficulties include delayed onset and slower acquisition of lexical and grammatical forms, smaller vocabularies, and difficulty acquiring and using inflectional morphology and complex syntax. By definition, LI is not a consequence of hearing loss, articulatory problems, neurological disease, or pervasive developmental disorders. LI has a genetic component and is associated with ADHD and dyslexia later in life (Catts, 1993). Due to high prevalence (Leonard, 1997) and maximal disability during the age of intensive learning, LI poses a significant personal and societal burden (The Agency for Healthcare Research, 2002).

Three broad theoretical accounts have been offered to explain LI. The "higher-order" account implicates representational or procedural problems in language-specific capacities such as access to innate features of grammar, computation of implicit grammatical rules, or verbal or phonological memory (Montgomery, 2003; Rice, Wexler, & Redmond, 1999; Ullman & Pierpont, 2005). The "lower-level" account implicates language non-specific deficits, including problems with temporal and spectral encoding of sensory information as well as with information processing speed (Lowe & Campbell, 1965; Tallal & Piercy, 1973; Tallal & Piercy, 1975). The third account suggests maturational delay (Bishop & McArthur, 2004,2005 McArthur & Bishop, 2004b; Wright & Zecker, 2004). This study addressed the latter two accounts, which are briefly reviewed below.

1.1. Temporal processing in LI

The first models concerning sensory origins of LI suggested a temporal processing deficit, predominant in the auditory modality (Lowe & Campbell, 1965; Tallal & Piercy, 1973; Tallal & Piercy, 1975; Tallal, Stark, Kallman, & Mellits, 1981). Studies that gave rise to this model used auditory repetition and temporal order

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judgment tasks and found that children with developmental dysphasia (LI) were poor at discriminating or making sequence judgments about non-verbal stimuli, vowels, or consonants when the stimuli were presented at a fast pace or when they were brief in duration, but performed within the typical range when stimuli were presented at a slower pace or were longer in duration (Tallal & Piercy, 1973; Tallal & Piercy, 1974; Tallal & Piercy, 1975). Initially, it was concluded that it was "the brevity, not transitional character", of auditory stimuli that challenged individuals with LI. Later, on the basis of findings that performance of children with LI was poor with consonant–vowel (CV) syllables but not with vowels of corresponding duration, it was proposed that the problem was caused by the transitional character of CV acoustics, containing rapidly changing frequencies, as well as a possibility of backward masking within a CV syllable (Tallal, Merzenich, Miller, & Jenkins, 1998; Tallal, Stark, & Mellits, 1985a; Tallal, Stark, & Mellits, 1985b). The backward masking hypothesis received support from several studies reporting that children with LI showed a disadvantage, compared with typically developing children, in detecting test tones specifically when they preceded a masking tone (Marler, Champlin, & Gillam, 2002; Wright et al., 1997).

Subsequent studies attempted to further characterize temporal processing as well as clarify its role in language abilities in LI. Bishop, Bishop, et al. (1999b) studied heritability of auditory deficits, as assessed by an auditory repetition task (Tallal & Piercy, 1973; Tallal & Piercy, 1974), in 37 twin pairs that included 55 7–13-year-old children with LI. This study found that performance on auditory repetition was poorer in the group with LI; however, this deficit was not influenced by stimulus presentation rate (inter-stimulus intervals of 10–70 ms vs. 500 ms). Further, Bishop, Carlyon, Deeks, and Bishop (1999a) administered three tests of temporal processing to 8–10-year-old children with LI, their six co-twins, and typical peers (total $n = 28$). Backward masking (also in McArthur & Bishop, 2004b) and temporal frequency modulation thresholds showed reliable correlations with auditory repetition scores administered 2 years previously; however, these thresholds showed no relationship with language abilities. Moreover, auditory repetition scores themselves correlated with non-verbal, but not with verbal, abilities. Therefore, while auditory repetition differentiated typically developing children from those with LI, it seemed to reflect abilities other than those directly related to language skills. Several other studies found no differences between children with LI and typical children in tasks requiring fast auditory processing, including tone detection during brief (40–64 ms) gaps in masking noise (Helzer, Champlin, & Gillam, 1996), discrimination of brief (20 ms) tones presented at very short ISIs (16, 32, 64 ms, and longer) (Fernell, Norrelgen, Bozkurt, Hellberg, & Lowing, 2002; Norrelgen, Lacerda, & Forssberg, 2002), or discrimination of brief frequency glides (Bishop, Adams, Nation, & Rosen, 2005). Furthermore, while the three latter studies found no problems with rapid auditory processing in children with LI, they found impaired discrimination of syllable pairs. Therefore, while the early results suggested temporal processing deficits in the LI, further research has failed to demonstrate a direct relationship between temporal processing problems and language abilities.

The three aspects of the temporal domain that have been suggested to pose a challenge for individuals with LI are stimulus brevity, transitional character, and fast presentation rate. While difficulty with brief stimuli could be caused by a slowed sampling rate, a time-domain property, problems with the transitional character of stimuli suggest a problem in a spectral domain.[1] Spectral sweeps are distinct acoustic features that are encoded by sweep-sensitive neurons in the auditory cortex (lateral belt). These neurons are tuned to specific "instantaneous" frequency and slope combinations, computed over brief time windows (Tian & Rauschecker, 2004). Therefore, the temporal sequence of instantaneous frequencies constituting a frequency sweep is encoded by multiple neuronal populations. The discrimination between two frequency sweeps, then, involves discrimination between two spectral representations encoded by two pools of neurons. Therefore, spectral processing appears to play an important role in processing of spectral sweeps, an essential feature of human speech and many environmental sounds. Finally, problems with rapid stimulus presentation rate refers to a temporal scale of hundreds of milliseconds (inter-stimulus intervals), which is least an order of magnitude longer/slower than the temporal scale involved in perception of brief individual sounds (the sound "brevity" account). Therefore, it is unlikely that these three deficiencies (problems with brief stimuli, transitional stimuli, and rapid stimulus presentation) originate from the same processing deficit. This may explain some of the apparent inconsistencies among the above-mentioned studies.

1.2. Spectral processing in LI

Interestingly, in the Wright et al. study (Wright et al., 1997), children with LI needed a larger frequency notch in the masking noise than their controls in order to overcome masking interference. This suggested diminished capacity of spectral resolution in LI. Consistently, several early studies by Tallal's group that were designed to address temporal processing had also found evidence for spectral processing deficits. Specifically, Tallal and Stark (1981) found that a group of 35 5–8-year-old children with LI had difficulty discriminating syllables /ba/ from /da/ with 40-ms CVTs and also syllables /sa/ and /sha/, in spite of a long (130 ms) duration of the fricative interval. Both of the above contrasts are spectrum-based. Further, Stark and Heinz (1996) found that perceptual similarity, and not the duration, of vowel stimuli made their discrimination challenging for children with LI. Finally, abnormal electrophysiological indices of detection of change in tone frequency (Holopainen, Korpilahti, Juottonen, Lang, & Sillanpää, 1997; Korpilahti & Lang, 1994), vowel (Shafer, Morr, Datta, Kurtzberg, & Schwartz, 2005), and CV syllable (Kraus et al., 1996) are also consistent with spectral processing in children with LI.

Both temporal and spectral perception in the same children with LI was examined by McArthur and Bishop (2004a), McArthur and Bishop (2004b, McArthur and Bishop (2005). These authors found that frequency discrimination thresholds were elevated in about one-third of children with LI, both for brief (25 ms) and long (250 ms) simple tones, complex tones, and vowels. Further, these thresholds correlated with non-word reading abilities and did not correlate with non-verbal abilities. Stimulus duration did not affect performance in either the typically developing children or those with LI, whereas the spectral stimulus complexity did (McArthur & Bishop, 2005). In general, vowels induced the highest discrimination thresholds in all groups. In addition, younger children with LI showed elevated discrimination thresholds, as compared with their peers, for vowels and complex tones. Therefore, McArthur and Bishop concluded that it is the spectral complexity, rather than phonemic nature, of stimuli that challenged the auditory system of children with LI. Consistent with this idea, Bishop et al. (2005) found that 9–12-year-old children with LI were not impaired on the discrimination of direction (up or down) of one-formant frequency glides, either as a function of glide's duration or frequency span. However, these same children performed more poorly than their controls on speech in noise discrimination. Therefore, behavioral and electrophysiological evidence suggests that children with LI have problems in the spectral processing

[1] In analogy to the visual spectrum of colors, the auditory spectrum refers to sound frequencies, their combinations, and derivatives, such as tone frequencies, vowel formants, or voice pitch.