Clinical Neurophysiology 128 (2017) 484–494

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Auditory brainstem responses to stop consonants predict literacy

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See Editorial, pages 480–481

ARTICLE INFO

Article history:
Accepted 5 December 2016
Available online 18 December 2016

Keywords:
Reading disorder
Auditory brainstem responses
Phonological awareness
Early diagnosis
Speech

HIGHLIGHTS

- Speech-evoked brainstem potentials convey the temporal precision of early speech sound encoding.
- Poor subcortical distinction related to poor literacy skills in 11–13-year-olds.
- Delta cross-phase could become a potential preclinical marker for the risk of developing dyslexia.

ABSTRACT

Objective: Precise temporal coding of speech plays a pivotal role in sound processing throughout the central auditory system, which, in turn, influences literacy acquisition. The current study tests whether an electrophysiological measure of this precision predicts literacy skills.
Methods: Complex auditory brainstem responses were analysed from 62 native German-speaking children aged 11–13 years. We employed the cross-phaseogram approach to compute the quality of the electrophysiological stimulus contrast [da] and [ba]. Phase shifts were expected to vary with literacy.
Results: Receiver operating curves demonstrated a feasible sensitivity and specificity of the electrophysiological measure. A multiple regression analysis resulted in a significant prediction of literacy by delta cross-phase as well as phonological awareness. A further commonality analysis separated a unique variance that was explained by the physiological measure, from a unique variance that was explained by the behavioral measure, and common effects of both.
Conclusions: Despite multicollinearities between literacy, phonological awareness, and subcortical differentiation of stop consonants, a combined assessment of behavior and physiology strongly increases the ability to predict literacy skills.
Significance: The strong link between the neurophysiological signature of sound encoding and literacy outcome suggests that the delta cross-phase could indicate the risk of dyslexia and thereby complement subjective psychometric measures for early diagnoses.

1. Introduction

1.1. Dyslexia

Dyslexia is a developmental reading and spelling disorder with a complex genetic architecture (Fisher and DeFries, 2002). The cumulative incidence rate is high with 5–12% (Shaywitz et al., 1990). Dyslexia persists in 4–6% of adults (Schulte-Körne and Remschmidt, 2003) disadvantaging employment, and compromising participation in daily life. Prevention requires early sensitive screenings that need to assess several cognitive domains as well as multiple senses because literacy acquisition evolves from the interplay between linguistic competencies, attention, memory, audition, vision, and gaze-control (Mcanally and Stein, 1996; Stein and Walsh, 1997; Carlisle, 2000; Snowling, 2001; Ahissar et al., 2006; Goswami, 2011, 2015; Carreiras et al., 2014; Lobier and Valdois, 2015). As a consequence, broad, time consuming test batteries are necessary to account for heterogeneous cognitive fingerprints that characterize various subtypes of dyslexia (Heim et al., 2008; Heim and Grande, 2012). An additional physiological

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http://dx.doi.org/10.1016/j.clinph.2016.12.007
1388-2457/

parametrization of involved processes offers several advantages. First, a differentiation of underlying physiological mechanisms combined with reliable behavioral measures could provide a better understanding of underlying mechanisms, and, thus, helps advancing theories, specifying treatments, and evaluating treatment outcome. Second, physiological features might be evident before clinical features emerge, and, thus, help detecting children at risk even before literacy acquisition. Third, early physiological diagnostic procedures that would not require an active cooperation of tested individuals would help to overcome uncertainties inherent to behavioral tests.

1.2. Dyslexia and the auditory system

The majority of individuals with dyslexia have phonological impairments (Bradley and Bryant, 1983; Wagner and Torgesen, 1987; Heim and Grande, 2012; Saksida et al., 2016), and, thus, struggle with the sound structure (Shovman and Ahissar, 2006). In addition, phonological awareness is deficient in individuals with dyslexia (Bruck, 1992). Phonological awareness is the awareness of and the access to the phonology of one's language (Mattingley, 1984; Wagner and Torgesen, 1987) as reflected, for example, in the ability to substitute the initial sound of a word (e.g. bee – tee, sound – round). Accumulating evidence links phonological difficulties and poor reading to auditory processing disorders (Goswami, 2011; Tallal, 2012). Poor psychoacoustic performance of individuals with dyslexia has been shown for various perceptive tasks, such as auditory discrimination (duration, frequency, or rise time) and detection of auditory modulation (amplitude or frequency) (for a comprehensive review see (Hämäläinen et al., 2013). This inaccurate auditory processing of temporal and frequency information is conjointly mirrored in irregular physiological correlates to speech and non-speech stimuli throughout the central auditory system (Kraus et al., 1996; Chandrasekaran et al., 2009; Schulte-Körne and Bruder, 2010; Díaz et al., 2012).

The current study links poor literacy to scalp-recorded brainstem responses and hereby to very early neural processes in the auditory pathway (Mcanally and Stein, 1996; Banai et al., 2005; Chandrasekaran et al., 2009; Strait et al., 2011). Complex auditory brainstem responses (cABRs) to speech or music stimuli reflect phase-locked activity of lower structures of the central auditory pathway, primarily the inferior colliculus, lateral lemniscus, and cochlear nucleus (Smith et al., 1975; Glaser et al., 1976; Sohmer et al., 1977; Skoe and Kraus, 2010; Bidelman, 2015). These cABRs reflect the synchronous firing of neurons to stimulus-related periodicities (Marsh et al., 1975). Peak latencies of these responses possibly encode fast transients of speech sounds (Johnson et al., 2008; Bidelman and Krishnan, 2010). Accordingly, cABRs capture the temporal precision of firing neurons in the auditory midbrain signaling high-fidelity and stability of early auditory encoding (Skoe and Kraus, 2010).

Characteristic fast transients of speech sounds are the distinct formant transitions of stop consonants and formant-related harmonics. Formants reflect resonance frequencies of the vocal tract that change with its shape and stiffness. Fast articulatory gestures such as opening the mouth for [ba] or lowering the tongue for [da], cause fast transitions of lower formants as shown in the spectrograms of the acoustic stimuli (Fig. 1). In the spectrogram of the syllable [ba], the first and the second formant rise during the first 50 ms. In contrast, for the syllable [da], the first formant rises, but the second formant falls. These formant transitions, in turn, constitute important spectrotemporal features that enable us to recognize and distinguish speech sounds.

Certain features of cABRs to these formant transitions co-vary with reading and phonological skills. Poor readers show unstable speech-evoked cABRs to the stop-consonant syllables [ga], [da], and [ba] (Hornickel and Kraus, 2013). Furthermore, poor readers and children with poor phonological awareness exhibit less distinct sound specific latency-shifts of certain peaks in cABRs to stop-consonant syllables (Hornickel et al., 2009). These latency-shifts are distinctive for sound-specific spectro-temporal features of the stimuli with earlier latencies for fast transitions in higher frequency bands (e.g. [ga] or [da]) and later latencies for fast transients in lower frequency bands [ba] (Johnson et al., 2008). However, the quantification of critical peak latencies requires a visual inspection of individual responses, and, is therefore, less objective and time consuming. A less time consuming and more objective metric that captures the brainstems ability to discriminate between spectro-temporal dynamic of speech sounds, such as stop consonants, is the cross-phaseogram. Time-varying frequency differences in speech stimuli display as phase shifts (Skoe et al., 2011) and emerge in the frequency spectrum covered by the phase-locking capability of the auditory brainstem. First evidence for a sensitivity of this measure to relate to phonological skills has been reported for preliterate children. Phase shifts were less distinct in 4-year-old pre-readers with poor phonological awareness (White-Schwoch and Kraus, 2013) compared to age matched peers with good phonological awareness. This observation led the authors to suggest that a potentially slower maturation of early auditory neural processes could hinder phonological development, and, thus, challenge later reading acquisition. Whether and how this physiological metric co-varies with literacy skills has not been investigated yet.

1.3. The present study

It remains open, whether the cross-phaseogram approach is sensitive to distinguish children with good literacy skills from children with poor literacy skills and how this metric co-varies with phonological skills in literate children. The present study tested whether the electrophysiological distinction of stop-consonants varies with performance in reading, spelling, and phonological awareness in children after at least 6 years of reading and spelling instruction. We recorded cABRs to synthesized syllables kindly provided by the Auditory Neuroscience Laboratory of Nina Kraus (Johnson, 1959; Skoe et al., 2011) in children that were former participants of the German Language Developmental Study (GLAD, e.g. Friedrich and Friederici, 2004). We quantified phase shifts to the [da] and [ba] syllable and tested expected relations to behavior: a reduced phase shift is associated with poor literacy skills as well as with poor phonological awareness. To keep the experimental burden on recruited teenagers arguable, we combined behavioral measures from the current and previous studies (Schaadt et al., 2016, 2015). Literacy was determined by averaging percentiles across a standardized German reading test and a standardized German spelling test. The results of the current study support theories on a pivotal role of the auditory system in literacy acquisition. The precision of speech coding in lower central auditory nuclei relates to the formation of phonological skills thereby constituting an important prerequisite of literacy acquisition.

2. Methods

2.1. Participants

Sixty-four native-German speaking children aged 11.4–13.8 (37 males) were recruited through the GLAD database (Friedrich and Friederici, 2004). Most participants took part in previous EEG studies on dyslexia (Schaadt et al., 2016, 2015). All children gave documented verbal assent; and all parents gave written informed consent prior to the experiment. Families received monetary