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Editorial

# A prolonged maturational time course in brain development for cortical processing of temporal modulations

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Binding of temporal information is beneficial for the whole repertoire of hearing functions such as sound localization, sound detection and sound identification. The concept of dynamic binding by synchronization of neuronal discharges has been developed mainly in the context of perceptual processing (Engel et al., 1999). Clearly, sensory systems (most evidences are coming from mammals) provide paradigmatic examples for functional architectures that give rise to binding problems in visual, auditory and memory brain systems (Engel and Singer, 2001). Moreover, significant results suggest that, in all these cases, the binding processes relevant for the instigation of awareness may be implemented in the temporal domain by transient and precise synchronization of neuronal discharges (Engel et al., 1999). Additionally, it has been suggested that the binding problem arising in distributed networks may be solved by a mechanism which exploits the temporal aspects of neuronal activity (von der Malsburg, 1994).

The primary goal of pediatric habilitation among audiologists and language pathologists is the development of age-appropriate language and reading skills so children can be educated. Therefore, all children with speech, language or learning disabilities should be assessed by an audiologist for hearing problems. Children diagnosed with hearing impairment should be provided remediation through appropriate cochlear implants(s), hearing aid(s), assistive listening device(s) or amplification system(s). While the role of audition is well understood, the role of auditory processing and auditory processing disorders (APDs) in the development of language and reading is more controversial. Auditory processing includes a variety of skills, which can be divided into several major categories (ASHA, 1996).

To better understand the impact of auditory processing and auditory processing disorders (APDs) on language and reading development, researchers have begun to evaluate auditory processing skills in children with known language and reading deficits such as in dyslexia. Dyslexia is defined as a language-based reading disorder that is primarily attributed to weaknesses in phonological processing. In an audiological way, most dyslexic children have normal hearing thresholds, but many may have an undiagnosed APD (Moncrieff and Musiek, 2002). Many researchers believed that dyslexia is not a visual or ordinary hearing problem but a flaw in a specific brain circuit that handles flowing auditory information in a rapid way (Habib, 2000).

APDs may be defined as weaknesses in perception and/or cognition following the input of an auditory stimulus. From initial neural firing at the receptor cells within the cochlea to the complex interactions that occur within the cortex, auditory processing occurs at many levels throughout the brain. Throughout early childhood, auditory structures in the brain depend upon innervation in the cochlea and ascending synaptic activity for normal development of neurons (Rubel and Fritzsch, 2002). Audiologists routinely assess five auditory processing categories: auditory closure, auditory figure-ground, binaural interaction, binaural integration and temporal processing. Because of a reported link between temporal processing deficits and deficits in phonics skills in reading impaired children, there has been a surge in research related to this topic (Tallal et al., 1993). Results from recent research efforts related temporal processing deficits in dyslexic children will impairments of temporal processing (Ben-Yehudah et al., 2004; Boets et al., 2007).

Another essential skill in auditory processing is temporal processing – the rate at which we can process auditory information. A person must be able to process auditory information at a rapid rhythm in order to develop appropriate listening and language skills. Audiologists have detected this in people with sensori-neural hearing loss for a long period of time and have referred to this concept as the "temporal window". It is well-known that if a person's "temporal window" is too large which means that the time period required to process sound is too long then it becomes more difficult for them to understand speech. Structural brain differences in areas involved in the rapid processing of hearing in affected people, and that people with these speech and learning disorders require 300 ms to process basic speech sounds, where normal processing takes about 25 ms (Tallal, 1980; Liégeois et al., 2014). Disorders of language and speech arise out of a complex interaction of environmental, genetic and neural factors. Until now, little is understood about the neural bases of these disorders. In participants with speech disorder, structural and functional anomalies in the left supramarginal gyrus suggest a possible deficit in integration or sensory feedback (Preston et al., 2014). In language disorders, cortical and subcortical anomalies were reported in a widespread language network, with little consistency across studies except in the superior temporal gyri (Hickok and Poeppel, 2007). Summarizing, both functional and structural anomalies are associated with language and speech disorders, including greater activity and brain volumes compared to healthy

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control group. The heterogeneity within and across participants and the variability in neuroimaging approach and samples restricts our full understanding of the neurobiology of these disorders and reducing the potential for designing novel interventions tailored at the underlying pathology (see Liégeois et al., 2014 for a review).

Temporal processing can be divided into two primary categories, temporal integration and temporal resolution (Eddins and Green, 1995). Temporal integration includes tasks in which the intensity and duration of the signal interact such as in threshold determination and signal thresholds during different types of masking. Temporal resolution includes tasks of temporal order judgment like the tone-order task used by Tallal (1980), but also includes gap detection, masking level difference, detection of amplitude modulation, and detection of temporal asynchrony.

Regarding temporal integration, when Rosen and Manganari (2001) asked the participants to detect a probe tone in the presence of a masking noise, they found that dyslexic teenagers performed similarly to control children with forward and simultaneous masking of the tones (Rosen and Manganari, 2001). To access the temporal resolution, pediatrics employ a battery of behavioral tasks. When tested on tasks of gap detection and binaural masking level difference, reading-disabled children aged 7–14 did not perform differently from non-impaired children (Breier et al., 2003).

Since first described by Tallal (1980), Temporal Order Judgment (TOJ) refers to the ability to correctly perceive the temporal ordering of stimulus such as auditory and visual (Tallal, 1980). Specifically, spatial TOJ measures the ability to correctly perceive the order of two tones presented to the two ears. Tests of the link between deficits in temporal order judgment and reading disorders have produced inconsistent results. Several researchers who failed to identify systematic differences in temporal order judgment (TOJ) between dyslexic and control children have suggested that large individual differences in performance on this task may be linked to verbal labeling skill rather than temporal processing (Marshall et al., 2001). On the contrary, Rey et al. (2002) added that TOJ performance in the dyslexic group also correlated with tests of phonological processing, lending substantial support to the rapid auditory deficit hypothesis.

To quantify the temporal asynchrony in children with reading disability, whether or not they had a co-morbid attention deficit disorder, researchers adopted one temporal acuity task involving the detection of a tone onset synchrony (Breier et al., 2003). The authors detected a poor performance of children with reading disability compared to controls and argued that the presence of a deficit on this temporal acuity task without evidence of any deficit on gap detection suggests sensitivity to backward masking in children with reading disorders.

Auditory processing disorder (APD) which is also known as central auditory processing disorder or CAPD) is a condition that makes it hard for kids to recognize subtle differences between sounds in words. It affects their ability to process what other people are saying (Bamiou et al., 2001).The number of children with APD is estimated to be 2–7% (Bamiou et al., 2001). Some experts estimate that boys are twice as likely as girls to have auditory processing disorder, but there's no solid research to prove that (Bellis, 1996). There are several kinds of auditory processing issues. The symptoms can range from mild to severe. Children with APD can have a weak ability to compare and distinguish between distinct sounds (auditory discrimination), to focus on the significant sounds in a noisy environment (auditory figure-ground discrimination), to recall what they have heard immediately or later (auditory memory) and to understand and recall the order of sounds and words (auditory sequencing) (Musiek, 1999). To establish that a child suffers from CAPD several factors with respect to language should be considered like adequate expressive and receptive language skills (Richard, 2007). It is important that children exhibiting academic and/or communicative difficulty be evaluated with respect to overall receptive, expressive language skills, cognitive function, psychoeducational/academic functioning and attention. This serves to improve the accuracy of differential diagnosis of CAPD and to determine the relative contribution of a CAPD to the child's overall difficulties (Bellis and Ferre, 1999).

The understanding of spoken language in human beings is strongly dependent on the information retrieved from the temporal "sound envelope" (amplitude of sounds) (Drullman, 1995; Drullman et al., 1994; Shannon et al., 1995; Smith et al., 2002; Han and Dimitrijevic, 2015). A well-known example is that the prosodic content of a spoken sentence is conveyed within the slow temporal fluctuations of the "sound envelope" (Rosen, 1992; Peelle and Davis, 2012).

To better understand the importance of temporal processing for speech perception, disorders known to alter the temporal processing of sounds should be studied such as auditory neuropathy (Starr et al., 1996) which results in the reduction of speech perception ability or by the adapt the temporal processing of speech perception ability via a cochlear implant (Shannon et al., 1995; Fu, 2002). Moreover, impairments of temporal processing has been associated with difficulties of language such as word deafness (Phillips and Farmer, 1990; Jorgens et al., 2008), dyslexia (Ben-Yehudah et al., 2004; Boets et al., 2007; Lehongre et al., 2011; Menell et al., 1999; Putter-Katz et al., 2005; Walker et al., 2002) and deficits in speech discrimination (Ali and Jerger, 1992; Souza, 2000).

Research interests of auditory temporal processing has been restimulated by recently proposed neurolinguistics models that suggest a significant role in speech perception for neural mechanisms relevant to encode the speech envelope (Giraud and Poeppel, 2012; Goswami and Leong, 2013; Gross et al., 2013; Peelle and Davis, 2012). According to these neurolinguistics models, the intrinsic brain oscillations play a pivotal role in the speech analysis by partitioning the continuous speech into simplified units and additionally to synchronize neural activity with the temporal rhythms of speech streaming (Giraud and Poeppel, 2012; Peelle and Davis, 2012). Speech is a dynamic signal that receives each type (prosody, syllables and phonemes) of critical information at quasi different time scales for example intonation/prosody at 500–1000 ms, phonemic features at 20–80 ms and syllables at 150–300. Therefore, the simultaneous sampling of these different speech temporal features should be realized by neural mechanisms. Poeppel (2003) proposed a temporal sampling model that suggest a "tuning" gating mechanism for intrinsic auditory cortical oscillations in the $\theta$ (3–7 Hz) and $\gamma$ range (30–50 Hz) to track and sample the syllables and phonemes respectively. As a logical output, those models that account for speech perception should be responsible for the maturation of temporal processing during the basic periods of language acquisition. Even though the study of the relationship between electrophysiological measurements and behavioral parameters in developing brain may provide insights to an objective set of criteria for normal speech perception, little is known about how sound envelope is processed through development.

Results from psychophysical studies based on behavioral evidences suggest that temporal processing of auditory stimuli undergoes a prolonged maturational time course. Performance of gap detection paradigm continues to improve within the range of 3–6 years (Trehub et al., 1995; Wightman et al., 1989) and reaches adult mature levels of performance by the age of 8–10 years (Davis and McCroskey, 1980; Irwin et al., 1985). Another example is the detection of amplitude modulations which reach mature levels at mid to late-childhood (Hall and Grose, 1994; Moore et al., 2011). Consistent results from many studies demonstrated poorer auditory temporal resolution for children compared to adults (Banai et al., 2011; Fox et al., 2012; Hill et al., 2004; Moore et al., 2011;