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Can emphasis on temporal processing inform literacy intervention design?

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ABSTRACT: The aim of this minireview is to explore the relationship between auditory (AP) and phonological processing and to probe potential 'cascade effects' on literacy development. The overall purpose of this study is to specify auditory deficits in language and literacy outcomes to inform intervention. Important underpinnings of language and literacy development and characteristics of AP, phonological processing, and phonological awareness in children with literacy disorders in light of auditory processing skills. Children with language and literacy impairments experience difficulties processing temporal and/or spectral changes in acoustic stimuli resulting from atypical neural synchronization. On a behavioural level, studies have revealed a relationship between temporal processing skills (e.g., rise time discrimination, frequency modulation sensitivity) and literacy development. While research remains inconclusive on intervention efficacy centred on auditory processing, this review serves as the stepping stone for investigating intervention methods focused specifically on temporal processing. Frameworks associated with literacy deficits and interventions may benefit from auditory modality-specific assessment and interventions.

Keywords: Auditory processing; Phonological processing; Language development; Literacy development; Literacy deficits

1.0 INTRODUCTION

Auditory processing (AP) is the perceptual processing of auditory information in the central nervous system (CNS) and the neurobiological activity that underlies that processing and gives rise to the electrophysiologic auditory potentials" (American Speech-Language-Hearing Association (ASHA), 2005). AP involves the auditory mechanisms responsible for discriminating speech and non-speech signals, sound localization and lateralization, auditory pattern recognition, temporal aspects of audition, and auditory performance with degraded and competing acoustic signals (ASHA, 1993, 2005; Bamiou et al., 2001; Bellis, 2003; American Academy of Audiology (AAA), 2010; Geffner & Ross Swain, 2018).

Other input processing skills necessary for academic and social success include auditory closure, immediate auditory memory, auditory working memory, phonological awareness/processing, auditory synthesis and integration, auditory cohesion, auditory conceptual function, and auditory comprehension, which all rely on an intact auditory processing system (Geffner & Ross Swain, 2018).

Auditory processing is crucial for communication, speech (Richard, 2011; Iliadou et al., 2015) and cognitive development (Corriveau et al., 2010). Information processing theory describes how information is processed via distributed and parallel networks with significant contributions from bottom-up and top-down factors (Massaro & Cohen, 1975). Bottom-up or data-driven factors pertain to the incoming acoustic signal and the integrity of the central auditory pathways. Top-down or concept-driven factors relate to higher-order central resources such as memory, cognition, attention, and language and their role in auditory information processing.

Given the complexity of the human brain and the sparsity of neuronal regions dedicated to single modalities, it appears that AP depends on more than just the hierarchal relay of acoustic features from the peripheral auditory system to the auditory cortex. Instead, the ability to process auditory information relies on two fundamental components: 1) how the neural representation of an acoustic signal is encoded through central auditory pathways and 2) how other higher-order functions affect fundamental sensory perception. Higher-order functions include attention, memory, experience, linguistic competence, executive function, and metacognition (Keith et al., 2019).

Professional and public awareness of deficits in auditory processing abilities remains relatively low. However, efforts have dramatically increased over the past two decades due to the collective aim of expert task forces convened by the American Speech-Language-Hearing Association (ASHA, 2005), American Academy of Audiology (AAA, 2010), and British Society of Audiology (British Society of Audiology (BSA), 2018), and the evolution of research studies directing attention to the understanding and identification of auditory processing deficits (de Wit et al., 2017; Schwonweiler et al., 2020; Ahmmed, 2020; Alanazi, 2023).

Greater efforts has yet to translate into greater clarity or clinician confidence regarding the aetiology, diagnosis, and management of disorders associated with AP. The relationship between auditory processing and literacy development in children with language disorders has also gained ground over the years (McArthur & Bishop, 2001; Vandewalle et al., 2011; Ghesquiere et al., 2014; Van Herck et al., 2021). This review addresses how auditory processing relates to phonological processing and literacy development.

Audiologists diagnose children with auditory processing disorders (APD) through specialized assessments focused on auditory discrimination, temporal processing, and auditory sequencing (ASHA, 2005; AAA, 2010). Speech-language pathologists (SLPs) contribute to this process by providing information about the child's language and communication skills, which helps understand the broader impact of a child's auditory processing deficits. SLPs play a crucial role in the interdisciplinary care of children with APD, focusing on therapeutic interventions and supporting functional outcomes (Jerger & Musiek, 2000; Kamhi, 2011; Richard, 2011).

SLPs collaborate with audiologists and other professionals to develop individualized intervention plans tailored to each child's needs. SLPs may implement auditory training exercises facilitating underlying auditory deficits (bottom-up), such as practising sound discrimination tasks, or remediating higher-order linguistic and cognitive skills (top-down), such as improving auditory memory through structured activities (Alanazi, 2023) SLPs also provide guidance and support to educators and families on how to create a conductive auditory environment and implement effective communication strategies to optimize the child's learning and social interactions (Jerger & Musiek, 2000). Research studies should continue to tease apart the effects of APD and the available interventions to empower SLPs with the knowledge and tools necessary to provide effective, individualized care for children with APD.

2.0 AUDITORY PROCESSING DISORDER (APD)

APD describes a deficit in the neural processing of auditory information along the auditory pathway. APD affects an individual's ability to acquire auditory skills adequately (i.e. detection, discrimination, identification, and comprehension of speech) (ASHA, 2005; AAA, 2010). These difficulties are further exacerbated in noisy environments. Though APD may coexist with higher-order deficits (e.g., attention deficit hyperactivity disorder [ADHD], learning disability, language impairment), it is not the result of these disorders (ASHA, 2005; AAA, 2010; Bellis, 2003). Additionally, it is worth noting that deficits in auditory, phonological, language, and cognitive processing can manifest similar overt behaviours and developmental outcomes across individuals (Sharma, 2006, 2009; Ghanizadeh, 2008).

Reported APD prevalence varies widely from 0.5% to 10% of the general population (Chermak & Musiek, 1997; Bamiou et al., 2001; Hind et al., 2011). In children, the estimated prevalence is between 0.2%-5% (Hind et al., 2011; Nagao et al., 2016). De Bonis (2015) noted a 2:1 male-to-female ratio in APD diagnoses. It should be emphasized that several factors may contribute to the variability in reported prevalence rates, such as the criteria used for APD diagnosis, the sample size evaluated, and the presence of comorbidities in the evaluated population(s).

APD may be related to a specific site of lesion or disorder, or the cause may be unknown. Predisposing factors and risk factors that may contribute to APD include genetics, neurological diseases (i.e. brain injury, tumours of the CNS, neurotoxins), otologic diseases (i.e. chronic otitis media), developmental delays, and prenatal/neonatal risk factors (e.g. anoxia, prematurity, hyperbilirubinemia, drug exposure, and cytomegalovirus) (Aristidou & Hohman, 2023). Most cases of APD in the pediatric population are thought to occur as a result of delayed central nervous system maturation or other developmental disorders, which may lead to any form of auditory deprivation (Musiek et al., 1990; Aristidou & Hohman, 2023).

APD can severely impact how children perceive, interpret, and respond to auditory information, which is essential for language acquisition and the development of communication skills. Research in this area has revealed that deficits in auditory processing can affect a child's ability to discriminate between speech sounds, process rapid changes in sound, and accurately perceive auditory sequences- all of which are fundamental for phonological awareness and language comprehension (Ferguson et al., 2011; Alanazi, 2023). Despite these insights, research gaps remain, particularly in understanding the long-term effects of untreated or subclinical APD on language and academic achievements. Addressing these gaps through rigorous research deepens our understanding of APD and enhances the development of effective interventions.

2.1 Early childhood indicators of APD and associated comorbidities

Characteristics among young children at risk for APD include poor rhyming skills, inability to follow songs and melodies, inattentiveness to the speaker when engaged in other activities, increased sensitivity to sound or noise, and difficulty processing complex directions. Language indicators also include difficulty formulating sentences, word searching, and recalling simple commands. Poor pragmatic skills often predict later language and social difficulties (Keith et al., 2019).

Corriveau et al. (2010) found that auditory processing influences reading acquisition by limiting the child's ability to extract phonological information from the speech stream. The two main components which form a speech stream are 1) the envelope (slow fluctuations of energy and frequency in a signal) and 2) the fine structure (fast changes of energy and frequency in a signal). A longitudinal study by Boets et al. (2008) revealed a significant relationship between envelope-level auditory processing and early literacy skills in preschoolers by measuring phonological awareness through rhyming and sound identification tasks.

APD symptoms may overlap with behaviour, attention, learning and/or language disorders (Riccio et al., 1994; De Wit et al., 2017). Several studies support high comorbidity rates between APD and other disorders. Given the similar behaviours and characteristics, comorbid disorders are often diagnosed in place of or in tandem with APD. Sharma et al. (2009) revealed significant co-occurrence between APD, reading disability, and language impairment. They assessed 68 school-aged children with suspected APD and nonverbal IQ of 80 or more for auditory, language, reading, attention, and memory measures. Results indicated that most children had APD based on the APD test battery, with the majority of deficits in pattern discrimination and dichotic listening tasks. Of these children, about half had difficulty within all three areas measured: AP, language impairments, and reading. There were modest correlations between a subset of measures of auditory processing and attention and memory. These results were in general agreement with Tallal's findings (2004).

A wide range of sensory, cognitive, social, and language skills are associated with the development and functionality of auditory processing, and there is ample evidence of the relationship between APD and language disorders (Iliadou et al., 2015; De Wit et al., 2016). Auditory assessment alone cannot distinguish APD from other disorders. Several studies have suggested a cross-modal approach (e.g. use of visual and auditory tests) to aid differential diagnosis; however, literature remains equivocal concerning the degree to which this approach is effective (Cacace & McFarland, 2005; Bellis et al., 2011). There is a general need for a multidisciplinary team to engage in appropriate assessment protocols and interventions.

3.0 PHONOLOGICAL AWARENESS: SKILLS AND DEFICITS

The ability to use speech sounds to transmit meaning depends upon the talker and the listener sharing knowledge of their language sound system at multiple levels of representation (Munson et al., 2005). There are four main types of sound system knowledge: a) articulatory, b) perceptual, c) phonological, and d) social-indexical. Articulatory and perceptual knowledge are both concerned with phonetic levels of representation. Phonetics studies the physical characteristics of sounds available for use in speech communication (Ohala, 1999). Phonetic knowledge includes parametric phonetics and phonetic encoding (Pierrehumbert, 2003). The parametric level of representation involves the physical reality of speech sounds—the production of speech with the vocal apparatus and the transmission of those sounds through the air to the ear of the listener. Phonetic encoding involves the abstraction of phonetic categories from the parametric phonetic space.

Phonological awareness (PA) is "the ability to reflect on and manipulate the structure of an utterance as distinct from its meaning" (Stackhouse & Wells, 1997). It is essential for developing reading and spelling (Gillon, 2005). PA is based on phonemic awareness, onset-time awareness, and syllable awareness and can be accessed via the detection, deletion, blending, and segmentation of phonemes, syllables, and clusters (Masso et al., 2014). Children's acquisition of phonological awareness is said to consist of three stages: 1) awareness of syllables and words, (2) awareness of onsets and rimes, and (3) awareness of phonemes (Goswami & Bryant, 1990). Perception of auditory cues affects the ability to acquire and develop these stages (Mayo et al., 2003). Children with speech difficulties typically find phonological awareness tasks difficult. The severity and type of speech impairment have been suggested as significant predictors of the performance of PA tasks (Sutherland & Gillon, 2007).

3.1 Auditory processing in children with phonological difficulties

Auditory processing difficulties in children with speech, language, and reading disabilities have been extensively explored in the literature. The literature surrounding this topic is complex because there is no consensus about the nature of the proposed auditory processing deficit, and studies do not consistently demonstrate auditory processing difficulties among children with language and reading disabilities (Hornickel et al., 2012). Furthermore, even when auditory processing deficits have been observed in these populations, non-sensory explanations cannot be ruled out, and causal relationships to the children's phonological processing deficits cannot be confirmed (Halliday & Bishop, 2006; Share et al., 2002). This degree of confusion leads readily to the conclusion that auditory processing difficulties may not be an essential causal factor in these disorders.

Speech perception deficits commonly occur in children with concomitant language and reading impairments and arise from multiple causes (Joanisse et al.,2000; Nittrouer & Burton, 2004; Jain et al., 2019). Based on animal models of neurological development, Ramus (2004) proposed a mechanism by which cortical ectopias lead to anatomical disruptions in thalamic nuclei, which are important for sensory processing. Interestingly, these top-down effects are relatively heterogeneous, where outcomes depend on the exact locations of the cortical ectopias and the mediating effects of hormonal conditions. The plausibility of this account does not rule out the possibility that some children suffering from an APD can consequently have speech perception and other phonological processing problems. It is noted that speech perception is learned, and a lack of optimum input from the language environment may limit the acquisition of appropriate cue-weighting strategies.

The development of auditory processing skills is vital in the first seven years of childhood as it strongly correlates with language development (Moore et al., 2012; De Wit et al., 2016). In addition, it is emphasized that acoustic processing is the basis for the reception of speech and the distinction of similar phonemes (Vanvooren et al., 2017; Jain et al., 2019). Acoustic reception and processing are prerequisites for accurately producing speech and literacy (Kamhi, 2011). Research evaluating the relationship between the auditory processing and phonological abilities of children with language disorders has shown that children with these disorders have poor auditory perception skills (Jain et al., 2019). It is hypothesized that disruptions in perception and expression of speech during phonological development may be due to impaired auditory processing (Sharma et al., 2009; Brancalioni et al., 2012; Jain et al., 2019).

The perceptual skills and behaviour of children with APD vary, as the deficit can be in any area of auditory processing (e.g., recruitment, coding, memory, and time processing) (Smoski et al., 1992). It is observed that children with APD also show deficits in language, PA, and cognitive functions (De Bonis, 2015). A child diagnosed with APD may have a listening divergence (De Wit et al., 2016).

Furthermore, APD can cause speech disorders due to interference with the established depiction of phonemes in the brain and speech discernment, thus making it difficult to learn the morphology and semantics of speech (Richard, 2011; Allen & Allan, 2013; Amaral et al., 2015). Children with APD have severe delays in phonological representation, suggesting that there is an issue in retrieving the phonological representations through auditory feedback during speech production (Lam et al., 2018). Temporal processing skills are crucial in PA and language development, particularly for speech perception and discrimination of similar-sounding consonants and other speech sounds (Vanvooren et al., 2010). It is hypothesised that a deficit in temporal processing led to exacerbated speech and language development difficulties in children with language disorders (Merzenich et al., 1996; Tallal, 1980).

4.0 CASCADE EFFECTS OF APD AND EFFECTIVE INTERVENTIONS ON LITERACY SKILLS

The complex reciprocal relationship between the auditory–oral and visual–written systems may explain how children who have problems with the auditory–oral system also present with difficulties learning to read and write (Milankov et al., 2021). Most professionals emphasize the importance of auditory processing in learning to read and its relationship with oral language skills and literacy development (Richardson et al., 2004; Vellutino et al, 2004; Ronen et al., 2018). In a bottom-up theory of reading, the auditory–oral system guides literacy development by underpinning the segmentation of printed words, decoding letters, matching them to a stored auditory model (phonetic and phonemic segmentation), and retrieving a corresponding word (lexical retrieval) (Schraeder & Seidel, 2020). The auditory component is based on a set of sounds combined to form spoken words comprising the receptive factors, whereas the oral and written modalities are the expressive factors.

Phonological awareness is a clinical marker for developing literacy skills, supporting bottom-up contributions to literacy development (Amadi, 2019). A relationship between deficits in PA and auditory processing has been postulated based on the premise that disruption in processing auditory parameters interferes with the stability of phonemic representation in the brain (Lam et al., 2018). Researchers have focused on evaluating this intricate relationship concerning later literacy achievement in special populations (De Wit et al., 2018; ElShafaei et al., 2022).

A profound etiological risk factor in dyslexic children found across languages is the disruption in the formation of phonological representations, resulting in unfavourable literacy outcomes (Swan & Goswami, 1997). It has been theorized that dynamic auditory cues and auditory temporal processing impairments contribute to phonological and literacy difficulties in children with dyslexia (Ghesquiere et al., 2014; Mittag et al., 2021). Law et al. (2017) conducted a longitudinal study examining the cascade effects of auditory processing deficits in children at familial risk of dyslexia from kindergarten to second grade. They assessed auditory processing measures such as rise time (RT), which involves discriminating the amplitude of signal envelopes, alongside phonological awareness (PA) and various literacy tasks. The study found that RT measured in kindergarten significantly influenced literacy development in grades one and two and showed positive correlations with phonological awareness skills in first graders.

Vanvooren et al. (2017) also demonstrated that cues embedded in the temporal speech amplitude envelope impacted later phonological and literacy skills, irrespective of familial dyslexia risk. These findings align with research by Boets et al. (2011), which highlighted significant contributions from frequency-modulation (FM) sensitivity and speech-in-noise perception to reading ability growth amongst first-graders. Conversely, there is variability in reports related to the link between auditory processing and language disorders, as several studies have not observed auditory processing issues in children with language impairments (Dawes et al., 2009; Hamalainen et al., 2013; Gokula et al., 2019). In a recent report, Drosos et al. (2024) indicated significant correlations between Speech Sound Disorders and Auditory Processing.

Several researchers have proposed theories to support the role of basic auditory processes in developing typical reading skills. Goswami (2010, 2019) proposed a temporal sampling framework for children with dyslexia to describe the atypical neural synchronization that occurs at slow-rate oscillations representing the envelope of speech input. This framework has been used to explain the harmful contributions of inaccurate neural synchronization to impaired speech perception and phonological and reading development in dyslexic children.

Studies examining temporal processing deficits in children with dyslexia have informed researchers on targeting intervention programs that directly focus on enhancing temporal processing and rhythm skills to improve phonological and literacy development (Flaugnacco et al., 2015; Harrison et al., 2018; Cancer et al., 2021). The use of envelope-enhanced (EE) auditory training was presented by a longitudinal study from Ven Herck and colleagues (2021), which revealed significant improvements in phonological skills and later reading abilities in kindergartners at risk for dyslexia.

A later study by Van Herck et al. (2023) investigated the impact of early intervention using phonics-based and envelope-enhancement (EE) training on neural synchronization at syllabic and phonemic envelope rates in children at risk for dyslexia between 5 and 7 years of age. The findings of this study did not reveal a significant impact of EE training on neural synchronization across children with dyslexia; however, the authors supported the notion of investigating auditory intervention focusing on temporal cues to aid developmental delay in literacy for children at risk for dyslexia. These efforts highlight the evolving understanding and potential avenues for intervention to address literacy development's auditory processing challenges.

5.0 CONCLUSIONS

Language and literacy disorders often relate to several determinants without specific causal relationships. However, it is important to have a clear understanding of what these determinants are and how they may differ within the population. Gaining insight into auditory processing skills in children with language and/or literacy deficits can guide the path to individualized intervention.

In this brief review, we investigated the relationship between APD, phonological processing and literacy development to clarify our understanding of how language and literacy development can be affected by auditory-related processes. Behavioural and developmental characteristics can manifest similarly amongst children with APD, language and/or reading disorders; therefore, it is important to distinguish their physiological differences. Auditory processing deficits are hypothesized to affect detecting acoustical changes in speech sounds among children with language impairment. Hence, this interferes with developing well-defined and robust neural phonological representations properly. This phenomenon has been observed in children with dyslexia. These children experience difficulties processing temporal and/or spectral changes in acoustic stimuli, resulting in atypical neural synchronization. Behavioural studies have revealed a relationship between temporal processing skills (e.g., rise time discrimination, frequency modulation sensitivity) and literacy development.

Several studies support a temporal processing framework behind deficits in speech processing, phonological development, and literacy development; however, research remains equivocal on the causal relationship. Moreover, there is plenty of variability in findings addressing auditory processing abilities in children with language and literacy deficits. Genetic and environmental factors, in combination with the complex demands of spoken language and reading, are the driving points leading to varying vulnerability across children. Researchers have proposed interventions focusing on auditory processing skills throughout the years; however, efficacy has yet to be generalized to children experiencing language-learning impairments.

Based on the conclusions drawn from this review, a multidisciplinary team, including audiologists, speech pathologists, special educators, and educational psychologists, should consider assessments that encompass auditory processing skills in children exhibiting language and/or literacy difficulties. This comprehensive approach is crucial for guiding individualized intervention strategies tailored to each child's needs. It is imperative for these professionals to accurately differentiate between auditory processing disorder (APD), language impairment, and dyslexia at a physiological level to ensure precise diagnosis and targeted treatment planning.

Given the suggested relationship between temporal processing skills, such as rise time discrimination and frequency modulation sensitivity, and literacy development, it may be useful for professionals to integrate assessments and interventions targeting these skills to enhance speech processing, phonological development, and overall literacy outcomes. Priority should be given to evidence-based interventions that focus on improving auditory processing abilities in children with language and literacy deficits while acknowledging the influence of genetic and environmental factors on individual variability.

Continued interdisciplinary collaboration among audiologists, speech pathologists, educators, and allied professionals is essential to ensure comprehensive care and optimize outcomes for children facing complex language and literacy challenges linked to auditory processing difficulties. Future research should aim to extensively review the literature surrounding intervention variability and efficacy for language and literacy development based on auditory processing frameworks.

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