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Review

Impairments of multisensory integration and cross-sensory learning as pathways to dyslexia

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ABSTRACT

Two sensory systems are intrinsic to learning to read. Written words enter the brain through the visual system and associated sounds through the auditory system. The task before the beginning reader is quite basic. She must learn correspondences between orthographic tokens and phonemic utterances, and she must do this to the point that there is seamless automatic 'connection' between these sensorially distinct units of language. It is self-evident then that learning to read requires formation of cross-sensory associations to the point that deeply encoded multisensory representations are attained. While the majority of individuals manage this task to a high degree of expertise, some struggle to attain even rudimentary capabilities. Why do dyslexic individuals, who learn well in myriad other domains, fail at this particular task? Here, we examine the literature as it pertains to multisensory processing in dyslexia. We find substantial support for multisensory deficits in dyslexia, and make the case that to fully understand its neurological basis, it will be necessary to thoroughly probe the integrity of auditory–visual integration mechanisms.

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1. Introduction

> *"A primary disturbance in the ability to integrate stimuli from the two critical sense modalities, hearing and vision, may well serve to increase the risk of becoming a poor reader"*
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> Birch and Belmont, 1963, p. 858

Learning to read is one of the great challenges faced by humans over the course of a lifetime of development. Given the

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enormous complexity of the stimulus set to be mastered, it is perhaps remarkable that the great majority of us manage to acquire this skill to such high degrees of proficiency. In fact, many will learn to do so in more than one language, and not an insignificant subpopulation will manage it in many more again, some of which are even acquired in adulthood. This multilingual reading involves the learning of correspondences between entirely novel orthographies and phonologies, which implies a remarkable degree of ongoing plasticity for what is ultimately a large-scale cross-sensory learning task. A significant minority of individuals, however, despite being of normal intelligence and having adequate educational opportunity and ostensibly intact audition and vision, will struggle and ultimately fail to adequately acquire this fundamental skill set. Developmental dyslexia is one of the most common learning disorders, affecting between 5 and 17% of the population in the United States (Shaywitz and Shaywitz, 2003; Shaywitz et al., 1998). A huge puzzle is why individuals who appear to learn perfectly well in other domains, have such difficulties when it comes to the task of matching orthographic tokens (letters and words) with phonological inputs. At its core, efficient reading requires the ability to form reliable cross-sensory associations between speech-sounds and letter combinations. In the initial stages of learning, the child labors to remember the correspondences, but as learning progresses, these correspondences begin to be automated until ultimately, the simple sight of a given orthographic token activates the phonological representation. In this sense, learning to read ultimately relies on the formation of automatic multisensory representations. What is more, we would contend that this relationship persists into adulthood such that the expert reader continues to rely on the engagement of these multisensory representations (Carreiras et al., 2014). It is our view, therefore, that a multisensory approach is essential to understanding the complex process of reading and deficits therein.

Considerable research efforts have been directed at understanding the processing deficits that lead to reading difficulty, and numerous theories regarding core deficits have been proposed (Vellutino et al., 2004). These include deficits in associative learning (Gascon and Goodglass, 1970), rule learning (Manis et al., 1987), selective attention (Pelham and Ross, 1977), and attention shifting (Hari and Renvall, 2001), as well as processing deficits specific to the auditory or visual sensory systems (higher level of *visual processing;* visual perception (Morgan, 1896), visual attention, (Valdois et al., 2004), or *low-level sensory processing*; magnocellular system (Eden et al., 1995; Stein, 2001) or auditory system (Hamalainen et al., 2012). One of the more consistent findings is a phonological deficit (Frost, 1998; Kovelman et al., 2012; Ramus and Szenkovits, 2008; Snowling et al., 2000; Wagner, 1986), although whether this is best attributed to a breakdown at the level of information storage, representation, or retrieval, and whether it represents a more general deficit or is specific to speech sounds, remains a source of debate (Goswami et al., 2011; Leppanen et al., 2012; Ramus and Szenkovits, 2008). While this work has certainly provided valuable knowledge of processing weaknesses that contribute to reading difficulty (for reviews see Hamalainen et al., 2012; Leppanen et al., 2012; Schulte-Korne and Bruder, 2010; Stein, 2001; Vellutino et al., 2004), consistent with the idea that there are many pathways to the dyslexia phenotype (aka "cognitive subtypes of dyslexia" (Heim et al., 2008)), none have led to a fully satisfactory accounting of the disorder. In turn, despite the fact that reading is arguably a fundamentally multisensory process, our knowledge of multisensory processing in dyslexia is remarkably limited. Here we review this literature, such as it is. Although this literature comprises a still relatively small body of work, it makes a compelling case for the importance of fully understanding the role that multisensory processing plays in reading, and the extent to which its impairment in turn disrupts the acquisition of fluent reading skills. We argue for the need to fully characterize the role of multisensory processing deficits in dyslexia; undoubtedly such information is needed for the development of optimized interventions that (1) enhance audiovisual multisensory processing, and (2) lead to the effortless integration of phonological and orthographic signals that we believe is key to successful reading.

2. Multisensory processing, reading, and dyslexia

2.1. Audiovisual correspondences

The very first published study on audiovisual processing in reading impaired children that we are aware of came from our own institution, the Albert Einstein College of Medicine. In this 1963 monograph Birch and Belmont stated "*among several possible causes for subnormality in learning to read could be a primary inadequacy in the ability to integrate auditory and visual stimuli*" (p. 853). Extending their work on the typical development of audio-visual processing, they tested the ability of children with and without reading disability to match sequences of tones to dot patterns. Participants judged whether the intervals between tones matched the spacing (short or long) between dots. They reasoned that the ability to map temporally distributed auditory information onto spatially distributed visual information was essential to the acquisition of reading proficiency. An impressive 150 children (boys only) between the ages of 9 and 10 who were reading impaired, and 50 age and gender matched controls, were tested. The reading impaired group was defined as children with an IQ above 80, and raw reading scores in the lowest 10% on at least 3 out of 4 reading tests (sentence reading, word knowledge, word discrimination, and reading). Individuals in the control group had raw reading and IQ scores in the normal range. The reading impaired group was significantly less accurate in matching sequences of dots and sounds, even when children with lower (but still normal) IQ were excluded from the analysis (Birch and Belmont, 1964). Although the contribution of unisensory processing differences was not accounted for in this study, this early finding on audiovisual processing in reading impaired individuals is intriguing (see (Widmann et al., 2012) for a basic replication of this study). The authors argued that the data support the role of audiovisual integration deficits in reading disorders. While explanations of differential performance across groups unrelated to multisensory processing are plausible, the Birch and Belmont study is remarkable for representing an early foray into probing audiovisual processing deficits in dyslexia.

Additional support for difficulties in the mapping of cross-sensory correspondences in dyslexia comes from the observation that early difficultly with naming letters is a strong predictor of dyslexia (Elbro et al., 1998; Gallagher et al., 2000; Lyytinen et al., 2006; Scarborough, 1990). Thus even the very initial stages of learning auditory–visual associations have been linked to reading success (Ehri, 2005).

2.2. Orthographic-speech sound integration

For obvious reasons, the majority of studies on multisensory processing in dyslexic populations have involved letter-speech sound stimuli. One of the earliest researchers on the role of letter-speech sound integration in dyslexia and typical reading was the late Leo Blomert from Maastricht University in the Netherlands. Using electrophysiology, he and his colleagues probed the development of the automatic processing of graphemes-to-phonemes (Froyen et al., 2008, 2009). Novice readers (2nd graders), mid-level readers (5th graders), and reading experts (adults) were repeatedly presented with the same matching letter-speech sound pair, or just speech sounds, while recordings of their brain activity were made. Sometimes the sound changed, resulting in a break in the auditory

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