General Introduction

Michael A. Skeide

Almost 150 years after Kussmaul's documentation of 'Wortblindheit' (word blindness) (Kussmaul 1877) the scientific community has generated a number of different theories of dyslexia and dyscalculia. While these theories are still controversially discussed, the converging findings of *longitudinal developmental research* now allow us to draw an increasingly clear picture of the potential origins of these learning difficulties. At the same time, the common understanding of dyslexia and dyscalculia is blurred by persistent myths, such as the notion that dyslexia causes letters to appear out of order or that dyscalculia is a sign of reduced intelligence. Moreover, families, educators, and even specialized practitioners are often not sure how a specific learning disorder is validly diagnosed and which type of support children need to cope with their difficulties. Accordingly, the purpose of this handbook is to provide a *developmentally grounded* perspective on these topics by integrating findings from the life sciences and social sciences.

Starting with the theoretical foundations of dyslexia and dyscalculia (Part I), we move on to key basic scientific questions, including cognitive, behavioural, genetic, environmental, and neural foundations (Parts II–IV). From there, fundamental discussions are centred on culture, gender, ethnicity, and socioeconomic status (Parts V–VI), before addressing applied aspects of prediction, intervention, and compensation (Parts VII–VIII). Finally, we focus on the best practice in diagnostics, prevention, schooling, and educational policymaking concerning dyslexia and dyscalculia (Parts IX–X). Together, the current work represents the field in its full width and across disciplines. Compact summaries at the end of each part will provide the reader with the essential take-home messages regarding what is known about dyslexia and dyscalculia.

The present book is intended to be a one-stop shop for anyone looking for an overview of the state of the art in the field, including researchers, instructors, students, policymakers, educators, teachers, therapists, psychologists, physicians, and, of course, those affected. To keep it accessible to such a broad audience, we took great care to minimize the amount of required prior knowledge of scientific concepts, research methods, statistical models, and technical terms. Furthermore, we tried to maximize its international relevance, wherever possible, by reflecting on the generalizability of the findings to individuals with different national, educational, and cultural backgrounds and by including the currently available literature on non-western-educated-industrialized-rich-democratic (non-WEIRD) populations.

PART I

Theoretical Frameworks and Computational Models

1 Theories of Dyslexia

Usha Goswami

1.1 Introduction

Dyslexia is a disorder of development. Classically, a child has shown apparently typical language acquisition and cognitive development until faced with the task of learning to read. Suddenly the child struggles: ‘In spite of laborious and persistent training, he can only with difficulty spell out words of one syllable’ (Hinshelwood 1896, p. 1378). Why this apparently specific problem with reading and writing? One hundred years later, a child with dyslexia aged 9 years wrote ‘I have blond her, Blue eys and an infeckshos smill. Pealpie tell mum haw gorgus I am and is ent she looky to have me. But under the surface I live in a tumoyl. Words look like swigles and riting storys is a disaster area because of spellings’ (I have blond hair, blue eyes and an infectious smile. People tell Mum how gorgeous I am and isn’t she lucky to have me. But under the surface I live in a turmoil. Words look like squiggles and writing stories is a disaster area because of spellings) (author’s private notes).

Theories of developmental dyslexia attempt to provide a systematic causal framework for understanding this specific learning difficulty. Most theories aim to identify the critical factor/s or ‘core deficits’ underlying the child’s struggle to learn, in order for remediation to be focused and effective. Yet there are a large number of theories of dyslexia, some mutually exclusive, and there is more heat than light. Many theories are over-reliant on data from a single language or a small set of languages, and no theory is universally accepted by researchers in the field. In this chapter, I focus on some of the most dominant theoretical frameworks, seeking points of unification. Importantly, I will adopt a *developmental* perspective, which means that theories and experiments relying on adult data will not be considered.

A focus on *development* is absolutely critical to identifying core factor/s for effective remediation. Currently, ‘multiple deficit’ theories of dyslexia are gaining in popularity (Pennington 2006; McGrath et al. 2020). A key developmental question is whether some of the multiple deficits, typically identified in studies of older children with dyslexia, are in fact a downstream developmental consequence of a single atypical factor present from birth that has had multiple systemic effects. Stringent research designs are required to identify such factors, as any deficits found once reading instruction has commenced may be a consequence of the severely reduced reading experience that is inevitable for dyslexic individuals. Both intervention studies and reading-level match studies can help to identify causal factors (Goswami 2015a), as can the study of typical learners.

A focus on development also requires consideration of sensory and neural data regarding how the typically functioning brain creates a speech processing system. Reading is essentially comprehending speech when it is written down. Accordingly, sensory and neural factors that cause individual differences in speech processing may play a role in the emergence of dyslexia. During the acquisition of spoken language, infants and children learn the sounds and combinations of sounds that are permissible in their language/s. Their brains develop *phonological representations* of the sound structures of individual words. As reading is learnt, these phonological structures are linked to visual codes. We know from infant research that phonological representations are developed via auditory, visual, and motor learning: phonological representations prior to reading are already multimodal (Kuhl 2004). Research testing theories of dyslexia must thus begin with infant studies. Taking a snapshot of a single sensory, neural, or cognitive parameter at one age point is insufficient, even with reading-level-match designs. Longitudinal studies beginning in infancy are the key to understanding causation.

To complicate the picture further, studies at multiple levels of developmental description in multiple languages are required. Researchers need to combine the assessment of individual differences in neural learning, sensory processing, cognitive processing, and children's behaviour in the same children, following these children over time using narrow age banding. Studies with pre-readers, including intervention studies, are particularly valuable. Theories that can identify factors for effective intervention prior to learning to read may offer the promise of eliminating dyslexia (Goswami 2020). Unfortunately, few current theories of dyslexia have been tested by studies that include all these important criteria. Nevertheless, these kinds of data will be my focus here.

1.2 Typical Development of Reading

If reading is defined as the cognitive process of understanding a *visual* code for *spoken* language, then, logically, individual differences in acquiring reading could be related developmentally to either spoken language processing or visual code processing, or both. Different cultures have invented a range of visual codes for representing spoken language, and skilled readers appear to access meaning directly from these visual codes. Nevertheless, *phonological activation* (activation of brain areas associated with linguistic sound-structure processing) is mandatory during skilled reading. This suggests that, developmentally, efficiency in learning a visual code cannot be separated from spoken language skills (see Figure 1.1). The visual code is not a neutral visual stimulus. It is a culturally specific code that is taught and learnt using symbol–sound correspondences. This learning typically begins a few years into the development of a spoken language system. The neural spoken language system is then changed forever by this symbol–sound learning. There is developmental *remapping* of phonology with the acquisition of print (Frith 1998).

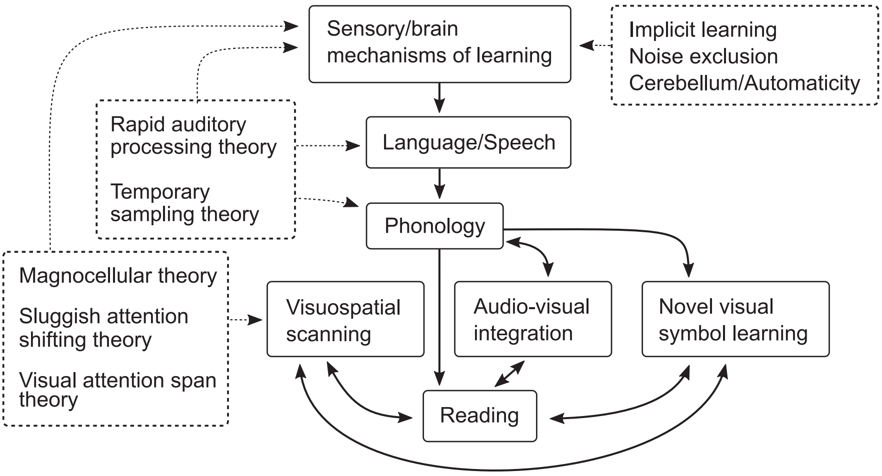

Figure 1.1 *Schematic depiction of key neural, sensory, and cognitive factors in learning to read, highlighting the core factors selected by different theories.*

For example, if young children are asked to choose pictures whose names begin with the same sound as 'truck', child readers will choose items like 'turkey' while preliterate children will choose items like 'chair' (Read 1986). Read argued that this occurs because the 't' sound in 'truck' is affricated and hence is phonologically closer to 'ch', a phonetic distinction still heard by the preliterate brain. Learning via print that the symbol used to represent the 'ch' sound in these words is 't' changes children's phonological judgements. Indeed, the young pre-readers studied by Read would misspell 'truck' as 'chrac' and 'ashtray' as 'aschray', errors that disappear as children learn conventional English spelling patterns.

As might be expected, brain imaging studies across languages show that symbol learning is linked to sound from the very beginning of acquiring reading (Blau et al. 2010; Froyen et al. 2009; Maurer et al. 2005; Maurer et al. 2011; Yang et al. 2020). The brain areas associated with phonological processing also show extensive developmental changes during the first two years of learning to read (Łuniewska et al. 2019). Further, spoken languages differ in the units of sound represented by the chosen visual coding system. For example, Japanese *Kana* represent individual syllables, Chinese *Kanji* represent morphemes, and the alphabet represents phonemes. Further while European languages such as Italian, Greek, and Spanish use alphabetic codes with highly consistent grapheme–phoneme correspondences, languages such as English, Danish, and French use markedly less consistent grapheme–phoneme correspondences (the 'consistency' problem; see Ziegler and Goswami 2005). When one letter can make multiple sounds, this slows learning for *all* children.

The development of 'phonological awareness' (the child's ability to consciously detect and manipulate the component sounds in words) follows a similar developmental sequence across languages. Phonological awareness also predicts reading acquisition in all languages studied to date. Phonological awareness has been called *metalinguistic awareness*, as its measurement depends on the child becoming *consciously aware* of knowledge that is already organized perceptually in her mental lexicon. The perceptual organization of speech information by a child (assigning acoustic, motor, or visual elements to the groupings comprising words in a particular language) contributes to individual differences in phonological representations. Awareness of syllables and onset-rimes (division of any syllable at the vowel, as in H-OP or ST-OP) appears to develop before learning to read across languages, whereas direct tuition is typically required to develop phoneme awareness. A child's access to stressed syllables, syllables, onset-rimes, and phonemes reflects their perceptual organization of the different 'psycholinguistic grain sizes' that comprise words (Ziegler and Goswami 2005). Interestingly, phoneme awareness develops at a faster rate for children who are learning to read orthographies with consistent grapheme–phoneme correspondences (Ziegler and Goswami 2005). This cognitive evidence that development itself changes the mechanisms and operation of the perceptual systems that support reading means that it is imperative to use rigorous longitudinal designs to test theories of dyslexia (see Figure 1.2).

The neural/sensory processes that underpin the development of phonological representations during spoken language acquisition are now better understood. Infants are sensitive to the acoustic boundaries that separate phonetic categories in all human languages, as are other mammals, birds, and insects (Kuhl 2004). This perceptual sensitivity is not equivalent to having conscious access to phonemes. The

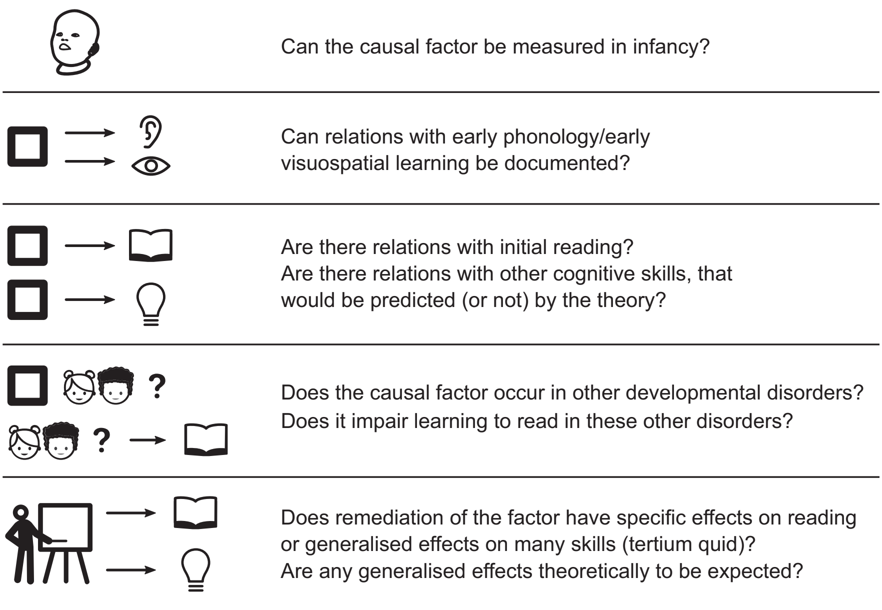

Figure 1.2 *Schematic depiction of key issues to consider when testing the evidence base for different theories of developmental dyslexia.*

infant brain also computes conditional probabilities between phonetic elements, syllables, and other speech sounds, thereby identifying possible 'words' (statistical learning; Saffran 2001). Some recent neurally driven work has revealed another important set of acoustic statistics that relate directly to phonological awareness at different psycholinguistic grain sizes. Statistical learning of interrelated changes in signal intensity (amplitude modulation) at different temporal rates in the speech amplitude envelope provides perceptual information relevant to extracting phonological units such as syllables and stressed syllables (Leong and Goswami 2015). Computational modelling of these amplitude modulation changes reveals that the different rates of amplitude modulation in speech are temporally dependent on each other (*phase dependency*). The amplitude modulations are also arranged in a hierarchy, with the slowest modulations governing the temporal timing of faster modulations. Computational modelling of both infant-directed speech and rhythmic child-directed speech (English nursery rhymes) shows that this amplitude modulation phase hierarchy by itself provides sufficient perceptual information for the brain to extract phonological units of different sizes with more than 90% efficiency (Leong et al. 2014, 2017). Accordingly, the acoustic statistical amplitude modulation structure of both infant-directed speech and rhythmic child-directed speech enables 'acoustic-emergent phonology' (Leong and Goswami 2015).

Neurally, we know that neuroelectric oscillations responsive to speech inputs (rhythmic changes in electrical brain potentials in large cell networks) are also hierarchically organized (Gross et al. 2013), and that the temporal rates of oscillation of these brain rhythms match the amplitude modulation rates in speech (Giraud and Poeppel 2012). 'Rise times' in amplitude (the rates of change between sound onset and sound peak in a given amplitude modulation) provide sensory landmarks that automatically trigger brain rhythms and speech rhythms into temporal alignment, via phase-resetting ongoing neural activity (Doelling et al. 2014). Accordingly, a nascent phonological system can be extracted from the speech signal via the automatic alignment of neuroelectric oscillations to the amplitude modulation information in speech, beginning in infancy (Goswami 2019a, 2019b). This automatic learning can, in principle, enable perceptual organization of the speech stream into syllable stress patterns, syllables, and onset-rime units. Importantly, for languages with consonant–vowel syllable structures, this automatic alignment for onset-rime units also yields information about single phonemes.

This brief survey of typical development suggests that comprehensive theories of dyslexia need to examine putative neural or sensory causes beginning from birth. I first review theories that attempt to explain the origins of the cognitive difficulties with phonology ('phonological deficit') that characterize dyslexia across languages. I then consider theories based on processing visual codes for spoken language, and finally I consider theories that utilize general properties of learning such as statistical learning and neural noise exclusion. In each case, I consider whether the theory is supported by longitudinal data, examine intervention and reading-level-match studies, consider whether the candidate deficit has been tested in other developmental disorders, and consider whether other cognitive difficulties predicted by the candidate deficit are present in children with dyslexia (see Figure 1.2). I also consider whether the available evidence draws on a range of languages.

1.3 Theories Explaining Individual Differences in Phonological Development

Auditory theories of dyslexia propose that sensory processing differences, present from birth, lead affected children to develop atypical phonological representations of spoken language. These impaired phonological representations then affect the efficient learning of a visual code for spoken language. As noted, visual codes for speech are not arbitrary visual stimuli; they are linked to phonology from the onset of learning. Accordingly, if the visual symbols being taught are difficult to match systematically to the perceptual organization of speech-based information in the child's mental lexicon, then learning to read will be slow and inefficient whichever symbol system is being acquired. I review two key theories proposing a sensory basis for the phonological deficit: one based on rapidly arriving pitch cues in speech and one based on slowly varying amplitude modulation-related information (Tallal 1980; Goswami 2011). As auditory learning begins in the womb (the amniotic fluid transmits the low-frequency amplitude modulation information in maternal speech), studies of infants and pre-readers are particularly important tests of causation.

1.3.1 Rapid Auditory Processing Theory

Rapid auditory processing (RAP) theory was first proposed by Tallal and Piercy (1973) to explain developmental language disorder and was later extended to dyslexia. The variations in frequency (pitch) that occur as a speaker moves from producing one phoneme to another are typically rapid (within 40 ms for formant transitions). The core theoretical proposal of RAP was that the ability to process this rapidly arriving and sequential acoustic information was impaired in developmental language disorder. Using tones of different frequencies, Tallal and Piercy showed that twelve children with developmental language disorder (aged 6.5–9 years) had difficulties in processing rapidly arriving information compared to chronological age-matched controls. In a subsequent study with dyslexic children aged 8–12 years, RAP problems were demonstrated in eight of twenty children compared to chronological age-matched controls (Tallal 1980). Accordingly, it was argued that difficulties in processing rapidly changing information in speech (such as the formant transitions that help differentiate phonemes) caused phoneme awareness deficits and thereby developmental dyslexia (Tallal 2004).

Given that conscious awareness of phonemes largely emerges as a consequence of learning to read, these acoustic difficulties should affect phoneme awareness in dyslexia across languages. However, this is not the case. For example, dyslexic 10-year-olds learning consistent alphabetic writing systems such as German become as accurate as chronological age-matched controls in recognizing and manipulating phonemes (Landerl and Wimmer 2000). RAP deficits are also found in a minority of Chinese