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REVIEW

The multiple-level framework of developmental dyslexia: the long trace from a neurodevelopmental deficit to an impaired cultural technique

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Abstract Developmental dyslexia is a neurodevelopmental disorder characterized by an unexpected impairment in literacy acquisition leading to specific poor academic achievement and possible secondary symptoms. The multi-level framework of developmental dyslexia considers five levels of a causal pathway on which a given genotype is expressed and hierarchically transmitted from one level to the next under the increasing influence of individual learning-relevant traits and environmental factors moderated by cultural conditions. These levels are the neurobiological, the information processing and the skill level (prerequisites and acquisition of literacy skills), the academic achievement level and the level of secondary effects. Various risk factors are present at each level within the assumed causal pathway and can increase the likelihood of exhibiting developmental dyslexia. Transition from one level to the next is neither unidirectional nor inevitable. This fact has direct implications for prevention and intervention which can mitigate transitions from one level to the next. In this paper, various evidence-based theories and findings regarding deficits at different levels are placed in the proposed framework. In addition, the moderating effect of cultural impact at and between information processing and skill levels are further elaborated based on a review of findings regarding influences of different writing systems and orthographies. These differences impose culture-specific demands for literacy-specific cognitive procedures, influencing both literacy acquisition and the manifestation of developmental dyslexia.

Keywords Phonological awareness · Cognitive abilities · Precursor functions · Alphabetic vs. non-alphabetic scripts · Grapheme complexity · Reading disability

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Reading, dyslexia and culture

In most societies around the world, reading and writing skills are prerequisites for full participation in social and professional interactions and access to cultural resources. Therefore, these key cultural techniques are taught through systematic instruction. During the procedural learning process triggered by this systematic instruction in an individual, pre-existing cognitive functions from different domains,

such as visual and auditory processing as well as memory, motor and language abilities, are modified and coordinated to form literacy-specific cognitive procedures (Lachmann, 2002, 2008, 2018; Lachmann & van Leeuwen, 2014). After long and intensive training, these procedures become automatized (Froyen et al., 2009; Lachmann & van Leeuwen, 2008; Nicolson & Fawcett, 2007, 2018), which is linked to structural and functional changes in the brain (Dehaene & Cohen, 2007). As a consequence, specifically formed cortical networks (Dehaene et al., 2010; Rueckl et al., 2015) are automatically activated for various *literacy-specific demands*. This can be considered as an *acculturation of the brain* (Huettig, Kolinsky, & Lachmann, 2018a; see also Posner & Rothbart, 2017). Following the principles of a feedback loop, acquiring skilled literacy has a reciprocal impact on the pre-existing functions recruited for the procedure, for instance on pre-existing phonological (Goswami & Bryant, 1990; Wimmer et al., 1991; see Huettig et al., 2018b, for review) and visual information processing (Ventura et al., 2008), memory (Kolinsky et al., 2020), as well as oral language abilities (Konerding et al., 2020; Tarone & Bigelow, 2005). Individual differences in these precursor information processing abilities lead to considerable variance in how well and how fast children learn literacy skills in the early school years. Besides these literacy-relevant precursor functions, other individual and environmental factors as well as their multiple interactions may contribute to the variance in the process of literacy acquisition. Such factors include differences in more general learning-relevant personality traits as well as cultural differences such as the orthographic system (Paulesu et al., 2000), curricular standards or socioeconomic conditions.

Apart from the described interindividual differences in literacy acquisition, most children learn to read and write in primary school without major problems. Some children, however, show persistent and severe difficulties in doing so, even though they do not have general learning problems. In practice and science, this specific learning disorder is generally termed *developmental dyslexia*. In international classification systems (Classification of Diseases and Related Health Problems, ICD, published by the World Health Organization, 2019, and Diagnostic and Statistical Manual of Mental Diseases, DSM, published by the American Association of Psychiatry, 2013) it is classified as a neurodevelopmental disorder. This clearly implies an underlying specific deficit in brain development during early childhood. Compared to a reference population, this deficit is considered to lead to severe impairments in later literacy acquisition. When following the classification systems for diagnosis of this disorder, according to Lachmann, Bergström, Huber, and Nuerk (2022) five *diagnostic features* must be considered: The (1) *severity* of this impairment must be evident on the basis of the individual performance in a standardized literacy test. These difficulties are (2) *persistent*, i.e., distinct from temporary performance fluctuations or from a delayed but adequate acquisition, and starting in childhood, following a defined pattern of trajectory and progression across the lifespan. The (3) *specificity* of the impairment must be confirmed by an unimpaired general cognitive development proven by a standardized test. Furthermore, the difficulties must be (4) *unexpected* given adequate instruction, psycho-social conditions and individual factors, including a sufficient mastery of the language of instruction, normal or corrected-to normal vision and hearing, and the absence of neurological disorders. Finally, these difficulties must (5) *manifest* as poor academic achievement in language related subjects with other subjects being less affected, except as secondary symptoms or in the form of diagnosed comorbidities (for an overview, see Lachmann et al., 2022).

These five diagnostic features, derived from classification systems, raise a number of issues. A very fundamental one concerns the fact that the neurodevelopmental deficit underlying the definition is not directly considered for diagnosis and, in practice, can hardly be directly measured on an individual basis. Rather, the diagnostic features focus mainly on impairments in reading and writing performance, i.e., on symptoms, and the neurobiological basis can only be inferred indirectly (e.g., considering time course and the highly controversial double-discrimination criterion, see Lachmann et al., 2022, for review). In principle, all features could also show up without a neurodevelopmental deficit being present. This is a major criticism of the neurobiologically based categorical definition of developmental dyslexia by many researchers, who argue that it merely represents the lower tail of a normal distribution of literacy skills in a population (e.g., Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Stanovich,

1994; for review and discussion see Elliott & Grigorenko, 2014; Lachmann et al., 2022; Stein, 2018a). Another issue results from the inherently large variance in reading and writing performance during early literacy acquisition. It is statistically inappropriate to make a diagnosis based on below average performance at a time when measures of variance are so high. Therefore, a diagnosis is only appropriate after skills have progressed and the population variance is reduced. This makes early intervention rather difficult (Lachmann, 2018).

But even if it is accepted that developmental dyslexia is indeed caused by a neurodevelopmental deficit (for critical discussion see, e.g., Protopapas & Parrila, 2019), that deficit would then have to be very mild and very circumscribed to exclusively affect reading or writing to some degree, but nothing else except for comorbidities. But since there are no structures or functions in the brain that are evolutionarily specific to reading and writing, how then can a developmental deficit have such a specific effect? Is it even likely that there is a single specific neurodevelopmental deficit that causes a single specific pattern of deficits in cognitive precursor functions and subsequent impairments in reading and writing skills? In fact, empirical results speak of a rather heterogeneous pattern in individuals with developmental dyslexia (Burgess, Witton, Shapiro et al., 2018; Lachmann et al., 2005; Lachmann & van Leeuwen, 2008; see also Spinelli et al., 2009), and this pattern, in turn, cannot be distinguished from the pattern found in children whose reading and writing difficulties are assumed not to be neurobiologically caused, e.g., indirectly proven by lack of double discrepancy (e.g., Flowers et al., 2001; O'Malley, Francis, Foorman, Fletcher, & Swank, 2002; Share, 1996; Siegel, 1992; see Aaron, 1997, for a review). A certain neurodevelopmental deficit, moreover, does not necessarily have direct impact on literacy performance itself, but is rather mediated through precursor information processing functions that may impair the literacy acquisition process ("mind the gap", cf. Protopapas, 2014). Concerning these functions, there is actually broad agreement with respect to phonological processing that most, but not even all, individuals with developmental dyslexia show deficits here that impair their literacy acquisition. There is less agreement, however, on how these phonological processing problems and problems with other cognitive precursor functions are neurobiologically caused and whether they actually reflect exclusively this cause of, or at least also a consequence of, literacy impairments (Huettig et al., 2018b).

In the end, literacy acquisition must be understood as a very complex and long-term procedural learning process that is influenced by numerous individual learning preconditions and environmental factors, as well as their complex interactions. Only with a better understanding of this learning process as such is it possible to understand what has gone wrong in learners with developmental dyslexia and how the disorder can be diagnosed and treated. The reasons can be multifaceted. In principle, it can be anything that significantly impairs the optimal learning process under the given learning conditions for an individual. Thus, there is no point in arguing forever about disparate and exclusive theories of very specific deficits and their possible neurobiological sources, for which some studies find evidence but others fail. Rather, there must be a general framework into which all evidence-based theories on neurobiological causes, their transition to cognitive precursor functions and their impact on the literacy acquisition process can be implemented (e.g., Protopapas, 2014, Farmer & Klein, 1995; Frith, 1999; Pennington, 2006). For example, the seemingly endless controversy over possible deficits in temporal processing as a more brain-based primary cause of impairments in the precursor functions of literacy acquisition (e.g., Habib, 2000, 2021) and whether these precursor functions are affected either in the visual domain, the auditory, or cross-modal (see Becker et al., 2005; Martino et al., 2001; Meng et al., 2022; Stein, 2002; Stein & Talcott, 1999; see Stein, 2018b; Tallal, 1980 for overviews), becomes obsolete under the simple model of Farmer and Klein (1995; Klein & McMullen, 1999) because the various possible pathways are integrated. These authors assume that deficits in basal auditory or visual temporal processing can lead to phonological or orthographic deficits, respectively, which then may result in different symptoms of developmental dyslexia. They further argue, however, that phonological and orthographic deficits both can result from deficits other than in temporal processing.

Multi-level framework of developmental dyslexia

When arguing about the neurobiological origin of developmental dyslexia, one thing should be kept in mind: this origin is not sufficient nor decisive for diagnosis. Ultimately, the nature of the problem is that an important cultural technique is not learned to a satisfactory standard despite adequate instruction in school, leading to a selective failure in *academic achievement*. In practice, although diagnosis is based primarily on measures of below-average performance in literacy skills relative to the reference population (while measures of other cognitive skills are average), the assumption is that such skill impairments ultimately lead selectively to poor academic performance in related subjects. Thus, academic achievement and its importance in a society is most decisive, and a diagnosis of developmental dyslexia as a disorder (ICD, DSM) would not be made if these academic failures did not exist or if the deficient skills were not culturally and socially of utmost relevance. The assumption of an underlying specific neurobiological deficit only plays a role in distinguishing between a general and a specific disorder and in differentiating it from problems that are merely caused by individual or environmental learning circumstances. The causal path from a mild and circumscribed early neurodevelopmental deficit to low grades in literacy-related subjects, later in school, is long and a lot can happen in the process of transition (Lachmann et al., 2022; Pennington, 2006). Deficits must be considered at well-defined hierarchical levels, and it is important to see what it depends on if a deficit at the neurobiological level ultimately translates to the level of academic achievement. Frith (1999), for instance, proposed three separable levels: the biological, the cognitive, and the behavioral level (see also Pennington, 2006). Deficits at the cognitive level form a bridge, so to say, between deficits at the biological level and impairments at the behavioral level. The latter includes the whole phenotype of observable effects. Crossing of this bridge is moderated by environmental factors. The general approach can also be applied to other neurodevelopmental disorders (Frith, Morton, & Leslie, 1991; Morton & Frith, 1993, 1995). We have proposed a multilevel framework for neurodevelopmental disorders (Lachmann et al., 2022) that considers five levels of a causal pathway on which a given genotype is expressed and hierarchically transmitted from one level to the next under the increasing influence of individual learning-relevant traits and environmental factors, moderated by cultural conditions. These levels are the *neurobiological*, the *information processing* and the *skill* level, the *academic achievement* level and the level of *secondary effects*. In the following, we will specify this framework for developmental dyslexia (see Fig. 1). The various risk and protective factors at different levels within the assumed causal pathway affect the likelihood of exhibiting developmental dyslexia (see also probabilistic multiple deficit models, Pennington, 2006; van Bergen et al., 2014).

The long trace from neurobiological level to an impaired cultural technique

The initial condition for developmental dyslexia as a neurodevelopmental disorder is a genetic predisposition (Lachmann et al., 2022). This is evident mainly from molecular and twin studies (for reviews, see e.g., Church, Grigorenko, & Fletcher, 2021; Grigorenko, 2022; Malanchini & Gidziela, 2022). The heritability is substantial (e.g., Plomin & Kovas, 2005: 42–72%, Grigorenko, 2004: heritability of 41–74% in reading skills and up to 90% in reading-related abilities; for an recent review, see, Malanchini & Gidziela, 2022:

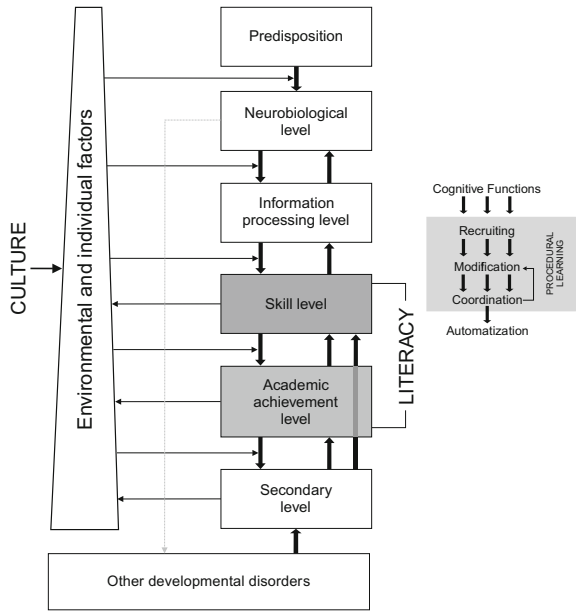

Fig. 1 Multiple-level framework for developmental dyslexia

34–41% in reading comprehension, and up to 70% in word decoding fluency). However, numerous *interacting* genetic and environmental risk factors are thought to underlie the deficit. In neurogenetic association studies, several candidate genes have been identified to be associated with an increased risk of developmental dyslexia (for an recent review, see Skeide, 2022). In addition, pre- and early postnatal environmental factors (e.g., maternal substance use or psychosocial stress) have been found to be associated with increased risk (for a review, see Hoeft & Bouhali, 2022).

Following the general principle of gene-environment interaction, the predisposition can lead to narrowly circumscribed developmental deficits at the first level, the *neurobiological* level. Due to the influence of environmental factors on this transition (see e.g., Mascheretti et al., 2018), in particular pre- and peri- and early postnatal protective and risk factors (e.g., breastfeeding, sufficient and healthy nutrition, stress and trauma, gestational weeks and birth weight, maternal smoking, risk of miscarriage; see also Hoeft & Bouhali, 2022, for a review), not all children with a genetic predisposition for developmental dyslexia may show a respective neurodevelopmental phenotype. For the same reason, not all children with developmental dyslexia can be identified with any genetic risk, for instance, a familial risk in terms of phenotypical effects evident in their parents.

The exact mechanisms (e.g., Galaburda, 1993b) of the transition from the genetic predisposition to a deficit at the neurobiological level remains controversial (e.g., Skeide, 2022; Skeide et al., 2015, 2016), as the latter, which is defined as the fundamental origin of the disorder, is not a *directly observable phenotype*. Therefore, indirect conclusions are typically drawn from resulting deficits in precursor functions or subsequent deficient literacy, or related research examines the transition more directly, e.g., post-mortem (see Galaburda, 1993a, for a review) or in mouse or rat models (see, e.g. Lampis et al., 2021, for review). One explanation is offered by the prominent neuronal migration abnormality hypothesis (Galaburda-Geschwind hypothesis; Galaburda et al., 1985; see Galaburda, 2002, 2018, for reviews), for example, of Magno cells in the cortex (Stein, 2018b). However, this hypothesis has been questioned more recently by knockout mouse models for some candidate genes that did not exhibit the expected cortical migration abnormalities (see Erbeli, Rice, & Paracchini, 2021; see Guidi et al., 2018, for review). Other researchers propose, for instance, neurodevelopmental deficits in the cerebellum (e.g., Fawcett, 2002; for a recent review see Li, Yuan, Luo, & Tao, 2022), in the insula (e.g., Richlan et al., 2009; Steinbrink et al., 2009), or in other cortical structures (see Braid & Richlan, 2022, for an short overview and Eckert, Berninger, Vaden, et al., 2016 or Richlan et al., 2009, for a meta-analyses), or deficits in the connectivity of relevant brain networks (e.g., Skeide et al., 2015; Tschentscher et al., 2019). Overall, research in the last decades indicates that complex neurodevelopmental disorders such as developmental dyslexia are highly polygenic, with many individual genetic factors having minimal effects on a rather heterogeneous phenotype (see Erbeli et al., 2021; see Skeide, 2022, for an overview).

Deficits at the neurobiological level may lead to impairments in literacy-relevant cognitive precursor functions at the *information processing level* (e.g., Farmer & Klein, 1995; Steinbrink et al., 2014). One prominent approach (Stein, 2019) assumes that deficits in the visual and/or auditory magnocellular processing systems leads to selective impairments in temporal processing of auditory and/or visual information (e.g., Farmer & Klein, 1995; Galaburda, 2002, 2018; Tallal, 1980; but see also Ramus et al., 2003a, 2003b) and other literacy-relevant cognitive functions, which can then disrupt phonological processing, speech perception (e.g., Catts, 1993), the interplay of transient and sustained visual channels throughout the brain (e.g., Stein, 2018a, 2018b) or fast visual recognition.

Another well-established approach is the Cerebellar Theory of developmental dyslexia (Fawcett, 2002; Nicolson & Fawcett, 2011, 2018; but see also Ramus et al., 2003a, 2003b; Savage, 2007), which postulates that a mild impairment in cerebellar development due to abnormal prenatal neural migration and/or in the functioning of complex cortico-cerebellar networks can, via different causal chains, lead to deficits in several precursor functions. Such functions include phonological awareness, phonological working memory and long-term memory, oculomotor functions and fast visual recognition (Fawcett & Nicolson, 2001; Nicolson & Fawcett, 2011) and also deficits in non-literacy-related functions typically observed in children with developmental dyslexia (but see also

Ramus et al., 2003a). Other explanations for the transition between neurobiological and information processing level assume impairments in the development of certain brain structures needed to build up literacy-related cortical networks (e.g., Peterson & Pennington, 2015; Pugh et al., 2000).

Regarding the relevance of precursor functions for literacy acquisition, there is broad agreement that various components of phonological processing (Wagner & Torgesen, 1987) are most significant (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Accordingly, meta-analyses confirmed deficits in individuals with developmental dyslexia in phonological awareness (Carioti et al., 2021; Melby-Lervåg et al., 2012), verbal short term memory and working memory (Carioti et al., 2021; Melby-Lervåg et al., 2012; Reis et al., 2020) and rapid automatized naming (RAN; Araújo & Faísca, 2019; Reis et al., 2020), but also in other than phonological precursor functions (e.g., Georgiou et al., 2021, 2022; Reis et al., 2020). These deficits have been demonstrated in a variety of languages and writing systems, although depending on cultural factors, particularly orthography (e.g., Landerl et al., 2013; Landerl et al., 2019; Landerl, Wimmer, & Frith, 1997; Reis et al., 2020, see section "Culture matters" below for further details).

The transition from the information processing level to the level of literacy skills starts with formal instruction and thus reflects a purely *culturally induced process*. As outlined in the Functional Coordination Framework (Lachmann, 2018), typically in a formally driven procedural learning process, relevant pre-existing cognitive functions are recruited, modified and coordinated to create the literacy-specific procedures (Lachmann & van Leeuwen, 2014) that form the basis for subsequent automatization (Nicolson & Fawcett, 2018). This complex and long-term learning process (see Fig. 1, right side) requires several years of intense practice (Froyen et al., 2009) and is associated with structural and functional changes in the brain (e.g., Dehaene et al., 2010; Dehaene, Cohen, Morais, & Kolinsky, 2015). That is why only from here we speak of literacy and of an *acculturation of the brain*. Note that the skill level does not just start after automatization. We define the literacy skill here not as an end product of this learning process, but as starting with any kind of *abstract*, instruction-related decoding, often termed literacy subskills or subcomponent skills (e.g., Cross et al., 2021; Solari et al., 2022). Examples of such include grapheme-phoneme conversion or pseudoword decoding in alphabetic orthographies, as it is already something that is not evolutionary determined and solely the consequence of a cultural invasion.

Deficits in literacy skill acquisition can arise in different ways: from impaired or inadequately modified cognitive functions required to create literacy-specific procedures, or from suboptimal coordination of these functions and/or poor/delayed automatization. For example, in alphabetic orthographies, insufficient suppression of the evolutionary based holistic processing preference in visual recognition (Lachmann & van Leeuwen, 2014), and/or deficits in phonological processing (e.g., Snowling, 2001) that impair the ability to identify and manipulate speech sounds (phoneme awareness), may lead to problems in functional coordination and thus in learning grapheme-phoneme conversion during the alphabetic phase of literacy acquisition (Frith, 1986). A deficit in functional coordination can lead to the automatization of a suboptimal procedure resulting in poor literacy skills. This, again, depends on individual learning-relevant environmental and individual factors (e.g., socioeconomic status [SES] or noise in the classroom; Calcus, Hoonhorst, Colin, Deltenre, & Kolinsky, 2018; Klatte et al., 2017).

Since cognitive functions and literacy reciprocally influence each other, deficient cognitive functions in individuals with developmental dyslexia can reflect both cause and consequence of impaired literacy skills (see, Huettig et al., 2018a, b; Peterson et al., 2018). For instance, in alphabetic orthographies, the acquisition of letter-sound correspondences and the related insight into the segmental structure of words contributes significantly to the improvement of phonological awareness (Landerl et al., 2019; Schmitterer & Schroeder, 2019; Ziegler & Goswami, 2005). Deficits in phonological awareness can therefore also be a consequence of using automatized sub-optimal literacy procedures (Klatte, Bergström, Steinbrink, Konerding, & Lachmann, 2018). To rule out the influence of literacy skills on precursor functions, a reading-level matched design (Goswami & Bryant, 1989; but see also Goswami, 2015; Zoccolotti, 2020) could be applied. The poor performance on phonological awareness and other precursor functions (e.g., short-term memory, see Melby-Lervåg et al., 2012; Parrila et al., 2020, for reviews) found in developmental

dyslexia samples in studies using such designs point to the causal role of these functions, without generally ruling out the possible reverse direction of effect in the population (Huettig et al., 2018b). Consistent with this interpretation, deficits in these precursor functions have been shown to precede literacy acquisition in a number of children, although not all, with developmental dyslexia (e.g. phonological awareness; Catts et al., 2017; but see also Landerl et al., 2019). Note, however, that some authors argue that more complex phonological processing abilities, such as phoneme awareness, may indeed be a good diagnostic indicator of developmental dyslexia, but more as a consequence than a cause, and may rather be understood in terms of an interactive phoneme awareness–literacy-relationship (see Landerl et al., 2019; Peterson et al., 2018). One shortcoming with reading-level matched designs is the possibility that—in the absence of group differences—a potential deficit at the information processing level has been compensated by higher metacognitive abilities in individuals with developmental dyslexia. In the end, in order really to establish causality, longitudinal and training studies are needed (Goswami, 2015). Such extensive studies, however, are rare.

Deficits at the skill level are assumed to lead to poor academic achievement in selective school subjects (and higher levels of education) in which literacy plays a primary role (*academic achievement level*) and a wide range of possible secondary symptoms (*secondary level*), such as emotional, behavioral and social problems. Regarding the latter, developmental dyslexia is, for instance, associated with a higher rate of depression, academic and social anxiety, lower emotional well-being, lower self-esteem and academic self-concept (mental representations of a person's own cognitive abilities), decreased motivation, and behavioral problems (for an review see Livingston, Siegel, & Ribary, 2018). Note, however, that these factors could also serve as individual risks for the transition up from information processing to the next levels, i.e., viewed at different levels, they can be both moderators and/or consequence for impairments at skill and achievement level. Crucially, secondary symptoms need to be distinguished from comorbidities that may result from shared or parallel neurobiological deficits, such as oral language, coordination, attention or math disorders (see Pennington, 2006; Habib, 2021, for reviews).

As emphasized above, for the diagnosis of developmental dyslexia, the failure at the achievement level is crucial. Again, this depends largely on individual (e.g., motivation, emotional and cognitive abilities and other learning-relevant traits) and environmental factors, both of which are influenced by cultural conditions. In this respect, studies showed the impact of teacher quality, quality of instruction (Taylor, Roehrig, Soden Hensler, Connor, & Schatschneider, 2010) and the level of parental education (e.g., Friend et al., 2008, 2009; but see also Kirkpatrick et al., 2011). Environmental factors at school (e.g., teacher attitudes and expectations related to developmental dyslexia or suitable supportive instruction) and at home (familial SES, parental support, home literacy environment) influence not only the extent of academic failure but also the probability and severity of subsequent secondary symptoms (see Haft et al., 2016; Livingston et al., 2018; Mascheretti et al., 2018, for reviews). Thus, the negative impact of developmental dyslexia on self-esteem depends on the degree of support at home (e.g., Carawan et al., 2016; Nalavany & Carawan, 2012; Singer, 2008).

In addition, individual learning-relevant factors influence how individuals with developmental dyslexia successfully proceed across the lifespan and the extent of secondary problems. Accordingly, individual "success attributes" (self-awareness, proactivity, perseverance, appropriate goal setting, effective use of social support systems, and emotional stability/emotional coping strategies) identified in a 20-year longitudinal study (Raskind et al., 1999) showed positive effects at the achievement level and also at the secondary level (Goldberg et al., 2003). For instance, more successful individuals with developmental dyslexia showed adaptive coping skills and subsequently fewer secondary symptoms because they were better able to deal with frustration, stress, and emotional problems (Goldberg et al., 2003).

According to the multi-level framework, the transition from one level to the next is neither unidirectional nor inevitable, which has direct implications for prevention and intervention strategies since these can mitigate transitions from one level to the next. This also means these strategies should not focus on one isolated level only and instead must consider the entire pathway. For instance, simply increasing reading and writing practice, i.e., training solely at the skill level, may have a positive effect only if modification and

coordination of unimpaired precursor functions at the information processing level has been achieved beforehand (Lachmann, 2018); otherwise, it is of little use because then a suboptimal procedure is simply further reinforced. On the other hand, an isolated training of identified deficient precursor functions may not be transferred to the skill level if the implementation of these in the re-organized procedure and its automatization is not promoted. The training of phonological awareness, for instance, has been shown to be effective when combined with a training of grapheme-phoneme correspondences and decoding skills (*phonics instruction*, e.g., Klatte et al., 2018; Konerding et al., 2020; for meta-analyses see Ehri et al., 2001; Galuschka, Ise, Krick, & Schulte-Körne, 2014; McArthur et al., 2018; but see also Bowers, 2020; Suggate, 2016), while isolated intervention by training of phonological abilities was not shown to be effective (e.g., Ehri et al., 2001). Note, however, that prevention programs targeting the promotion of deficient cognitive precursor functions (e.g., phonological awareness; see Ehri et al., 2001; Fischer & Pfost, 2015, for meta-analyses) at, or even prior to, the onset of literacy acquisition may improve later functional coordination and thus literacy acquisition and later school achievement (Tallal & Jenkins, 2018; see Hasselhorn & Schneider, 2022, for a review on prevention). Furthermore, interventions that focus on both improving academic performance and enhancing self-esteem may also reduce symptoms at the secondary level (e.g., McNulty, 2003). Accordingly, intervention programs that include the promotion of the aforementioned individual "success factors" (Goldberg et al., 2003) may be promising.

An important question is how to identify children at increased risk for developmental dyslexia who would benefit from prevention programs prior to literacy acquisition. Since diagnosis of developmental dyslexia is only possible after automatization at skill level (see Lachmann et al., 2022), in practice, intervention usually starts relatively late in primary school, although, as we argued, a training of precursor functions before literacy acquisition would be beneficial (Hasselhorn & Schneider, 2022). Therefore, one option for an earlier intervention is to use appropriate screening procedures to identify children who have deficits in the literacy-relevant precursor functions (particularly in phonological awareness) prior to literacy acquisition and then to provide targeted intervention. Another option is to consider the genetic predisposition to developmental dyslexia (e.g., familial risk) in prevention. Since children of parents diagnosed with a neurodevelopmental disorder are at increased risk of developing similar problems (Gallagher, Frith, & Snowling, 2000; McBride-Chang et al., 2011b; Snowling, Gallagher, & Frith, 2003; van Bergen et al., 2014) these may benefit from prevention programs that target the precursor functions and individual factors mediating dyslexia and the consequences at achievement and secondary levels.

Culture matters

Developmental dyslexia is recognized worldwide (for an overview see, e.g., Mather, White, & Youman, 2020), but there are large cultural differences between countries in dyslexia-related issues. Such differences include assessment practices and interventions, teacher knowledge, and attitudes toward developmental dyslexia (see Mather et al., 2020). Nevertheless, a recent meta-analysis (Yang et al., 2022) found no differences in prevalence rates of developmental dyslexia as a function of cultural factors such as the writing system and orthographic depth (even though prevalence estimates varied greatly between studies: 0.03–0.20). But this is actually quite obvious, given that the essential criterion for the diagnosis of developmental dyslexia is a deviance in skill performance relative to the respective reference population, and that the statistical criterion for this deviance is uniformly valid worldwide (usually 1.5 or 2 SD below the age norm, corresponding to 6.7 and 2.3 percent of the respective reference population). Thus, the prevalence rate is theoretically predetermined across cultures, while at the same time different writing systems impose quite different culture-specific demands for literacy-specific cognitive procedures (see Fig. 1).

Culture has a moderating impact via individual and environmental factors at and between all levels in the proposed framework. At the neurobiological level, for example, literacy-specific neural networks differ in unimpaired literacy development as a function of the writing system; but the structural and functional deviations found in developmental dyslexia also differ depending on the writing system (see, e.g., Li & Bi, 2022; Siok & Qin, 2022, for overviews).

In the following sections, we focus on cultural influences at skill level and on the transition between information processing and skill level due to varying writing systems and orthographies. Thereby, we will address these influences on both unimpaired literacy acquisition and developmental dyslexia (see also Daniels & Share, 2018).

Skill level: cultural differences in writing systems and their influences on literacy acquisition and developmental dyslexia

Language and orthography are essential cultural factors that influence both literacy acquisition and the possible manifestation of developmental dyslexia (e.g., Seymour, Aro, & Erskine, 2003; for reviews, see Verhoeven et al., 2019; Ziegler & Goswami, 2005). Literacy acquisition involves learning how spoken language can be expressed in a written system. This requires learning which spoken units are represented by which basic graphic symbols (graphemes). The representation of spoken units by graphemes varies between the different types of writing systems. Within each type of writing system there are yet different scripts (e.g., Latin and Cyrillic in the alphabetic writing system), which again have different orthographies in different languages (e.g., Latin script in English versus German orthography; see Hirshorn & Harris, 2022). According to Daniels (2017). Five different types of writing systems can be distinguished today: (1) *logosyllabary* or morphosyllabary (e.g., Chinese), in which every character represents a morpheme (often a word); (2) *syllabary* (e.g., Kana in Japanese), in which every character represents a syllable; (3) *abjad* (e.g., Arabic, Hebrew), in which each character represents a consonant; (4) *alphabet* (e.g., Finish, German, French, English), in which each character (letter) represents a consonant or a vowel; (5) *abugida or alphasyllabary* (e.g., *Kannada, Devanagari*), in which each character represents a consonant accompanied by a specific vowel. Note that in an earlier proposal, Daniels and colleagues (Daniels, 2003; Daniels & Bright, 1996) defined a further type, the *featural* script (e.g., Korean), in which the shapes of the characters indicate the phonetic characteristics of the segments they denote.

Other researchers distinguish only "three basic writing types according to their basic unit of mapping" (Perfetti & Harris, 2013, p. 297). These are: (1) *morpho-syllabic* or logographic; (2) *syllabic*, and (3) *alphabetic*, clustering together the three phoneme-based alphabetic writing systems (alphabets, abjads, and abugidas). Research on developmental dyslexia initially focused strongly on alphabetic writing systems, in particular on English and some western European languages (e.g., Share, 2014). Consequently, theoretical models of developmental dyslexia have often been based on findings from these alphabetic writing systems (for reviews of developmental dyslexia in other languages see, e.g., for Hebrew: Share, Shany, & Lipka, 2019; for Russian: Zhukova & Grigorenko, 2019). Meanwhile, however, there is also a growing number of findings from non-alphabetic writing systems (e.g., Chinese: Ho & Bryant, 1997; Hung, Frost, & Pugh, 2018; Tzeng et al., 2018; Devanagari: Skeide et al., 2017; Japanese: Wydell, 2019) and cross-orthography comparative studies designed to test the applicability of existing reading-related and dyslexia-related models in non-alphabetic languages (e.g., Joshi, 2018; Peng et al., 2021). In this context, an important question is whether the characteristics of typical and disordered reading are language specific or universal across different languages and orthographies (see Joshi, 2018; Landerl et al., 2013, 2019). In order to contrast the two extremes, we here consider findings on reading acquisition and developmental dyslexia in phonologically-based alphabetic writing systems and in the morpho-syllabic writing system of Chinese (for a review, see also Xu, Tan, & Perfetti, 2019).

There are considerable differences between different languages and writing systems regarding: (1) the *complexity of the spoken units*, (2) the *complexity of the smallest written units* (graphemes) and the corresponding size of the grapheme inventory (i.e., the number of letters or characters contained in a script), and (3) the *mapping* between spoken and written units, with differences in the language units (phonemes, syllables, syllabic morphemes) represented by graphemes, and in the consistency of the grapheme-to-sound mappings (see Siok & Qin, 2022; see also Daniels & Share, 2018, for an overview about variations in ten different dimensions of writing systems). Note that there is no consensus on the definition of the concept *grapheme* (see Meletis, 2019). Following Meleti's (2019) universal definition of a grapheme with three criteria, (a) lexical

distinctiveness, (b) linguistic value by referring to a linguistic unit such as phonemes, syllables or morphemes, (c) minimality, here we understand both letters or letter combinations in alphabetic writing systems and the single characters in the Chinese morpho-syllabic writing system as graphemes.

Regarding the (1) *complexity of the spoken units*, languages differ in tonal complexity, the number of phonemes (25 in Japanese/Spanish to over 40 in Thai/English), the syllable structure and the number of distinct syllables (from 643 in Japanese to nearly 7000 in English; see Coupé, Oh, Dediu, & Pellegrino, 2019). The complexity of syllable structures has an impact on the development of nonword decoding skills (Seymour et al., 2003). Languages with simpler syllable structures (e.g., Italian) consist predominantly of the open syllable structure CV (consonant–vowel) and only a few consonant clusters (VCC, CCV), whereas languages with a complex syllable structure predominantly have closed syllables and numerous initial and final consonant clusters (CCV [e.g., fly], VCC [e.g., its], CCVC [e.g., draw], CVCC [e.g., cold], CCVCC [e.g., plant], and CCVCC [e.g., skills]). In Seymore et al. (2003), nonwords were read more accurately and faster in simple syllable languages than in complex syllable languages, but there were no differences in reading familiar words depending on the complexity of the syllable structure. This could indicate that phonemes are more easily recognized in languages with a simpler syllable structure than in languages with more complex syllable structures (see Siok & Qin, 2022, for this reasoning). At this point, we have to make a turn to the information processing level, because phonological awareness is directly related to the perception of spoken language. In many languages, it has been found that phonemes in consonant clusters (e.g., in the complex syllable structures CCVC or CVCC) are more difficult to manipulate than single consonants (e.g., in the syllable structure CVC), both at the onset (e.g., the/t/in 'tree' vs. the/t/in 'tea') and in the codas (e.g., the/t/in 'left' vs. the/t/in 'let', see Caravolas & Landerl, 2010, p. 468). Interestingly, Caravolas and Landerl (2010) found a language-specific effect of syllable structure. Czech children, whose language has a much greater frequency and variety of complex syllable onsets compared to codas, were consistently more accurate and faster in isolating phonemes in onsets than in codas. In contrast, German children whose language has a more balanced distribution of onsets and codas and in which there are more complex codas than in Czech, were more accurate (but not faster) at phoneme isolation in codas than in onsets. The authors concluded that exposure to the syllable structure of the native spoken language plays an important role in forming children's phoneme awareness. In addition, there is evidence that the complexity of the syllable structure has an impact on phoneme awareness deficits in developmental dyslexia, although the influence of syllable structure is not found in all tasks (Jiménez et al., 2005). Spanish children with reading difficulties showed deficits in the deletion task compared to age-matched readers for words with a complex syllable structure (CCV), but not for words with a simple syllable structure (CV). However, these differences in the deficits depending on syllable structure were not evident in the isolation task. More research regarding the influence of syllable structure on typical and impaired reading is needed, as the influence of oral language structure on the development of phoneme awareness is still understudied (see Caravolas & Landerl, 2010).

Regarding (2) *differences in written units*, the visual complexity of graphemes also varies across languages from quite visually simple letters in alphabetic orthographies to highly complex characters in other orthographies (e.g., Chinese, Japanese with characters with 10 or even more strokes, see Chang et al., 2018; Chang et al., 2016; see Verhoeven & Perfetti, 2022, for an overview on orthographies of different visual complexity, measured by five different complexity measures). Strongly related to grapheme complexity is the size of the grapheme inventory and the language units represented by graphemes, which also depends on the type of writing system (Chang et al., 2016, 2018; Verhoeven & Perfetti, 2022). The larger the units represented by graphemes (phonemes, syllables, syllabic morphemes), the larger the size of the grapheme inventory and, consequently, the more complex graphemes are required to provide enough visually distinct graphemes (see Chang et al., 2016; Miton & Morin, 2021; Verhoeven & Perfetti, 2022).

The larger the grapheme inventory, the more time is needed to learn the visual forms of a writing system (see Chang et al., 2016; Verhoeven & Perfetti, 2022). In alphabetic orthographies (20–45 graphemes), nearly all letters (graphemes) are learned by the end of first grade with only minor differences in mastery

level between languages (90% accuracy in Dutch to 99% accuracy in Swedish; Seymour et al., 2003). In alphasyllabic orthographies, about 4 years are needed to learn all graphemes (e.g., over 400 graphemes in Kannada; Nag, 2007, 2014). In morphosyllabic orthographies (average number of graphemes: > 3000, see Chang et al., 2016; e.g., Chinese with several thousand characters, McBride et al., 2022; Verhoeven & Perfetti, 2022), not all graphemes are mastered even after 6 years of formal instruction (Shu et al., 2003). Thus, the size of the grapheme inventory dramatically impacts reading acquisition. Moreover, as will be elaborated later, the impact of different precursor cognitive functions on reading acquisition and reading skills depends on the complexity of the graphemes and the units represented by the graphemes (see, e.g., Landerl et al., 2022; McBride et al., 2018, for an overview). However, Chinese is not only special in terms of the size of the grapheme inventory and the complexity of the characters, but also poses the challenges that many characters correspond to the same syllable and that the phonological information (indicated by a phonetic radicals) is not reliable (Shu, 2003; Tan et al., 2005). Note that Chinese characters usually represent monosyllabic morphemes, and that most of them are ideophonetic (semantic-phonetic) compounds with both semantic (providing information about the meaning) and phonetic radicals (indicating the pronunciation; see Shu et al., 2003, for further explanations).

Finally, the (3) grapheme-to-sound *mappings* can vary greatly between different writing systems. Alphabetic orthographies differ, for instance, in the consistency in which graphemes are mapped to phonemes (grapheme-phoneme correspondence), also referred to as transparency or orthographic depth (Frost et al., 1987; Ziegler et al., 2010). In transparent (or shallow) orthographies, largely consistent one-to-one relationships are found between graphemes and phonemes, leading to the pronunciation of phonemes being approximately the same for different words. In opaque (or deep) orthographies, in contrast, the pronunciation of a grapheme varies across words (e.g., in English: *a* in *car, hat, late, want*). In cross-language or cross-orthography studies (e.g., Landerl et al., 2013; Reis et al., 2020), the different orthographies are typically assigned to three levels of complexity with respect to feedforward and feedback consistency of grapheme-phoneme and phoneme-grapheme correspondences, based on the classification of Seymour et al. (2003). In opaque orthographies (e.g., Danish, English, Hebrew) with the highest level of orthographic complexity there are inconsistencies in grapheme-phoneme correspondences (low feedforward consistency) and in phoneme-grapheme correspondences (low feedback consistency). In contrast, in transparent orthographies (e.g., Spanish, Italian, Finnish) with the lowest level of orthographic complexity, the feedforward and the feedback consistency are high. Orthographies with intermediate complexity level (Dutch, German, Swedish) have highly consistent grapheme-phoneme correspondences (high feedforward consistency), but less consistent phoneme-grapheme correspondences (low feedback consistency), or the reverse. Other authors (e.g., Borleffs et al., 2017) assume that orthographic transparency can be regarded as a continuum ranging from predominantly transparent orthographies (e.g. Finish) to the opaque orthography English with many different mixes in between.

The speed and difficulty of reading acquisition depends crucially on the transparency of the mapping in a writing system. In relatively transparent orthographies (e.g., Greek, Finnish, Italian, German), grapheme-phoneme correspondences are easy to recognize and to learn because of their regularity. In contrast, it is more difficult to acquire grapheme-phoneme correspondences in opaque orthographies because different phonemes are often assigned to the same grapheme. Accordingly, word reading accuracy reaches the skill ceiling usually by the end of the first year of school in opaque orthographies (e.g., Finnish, Italian, German), while word reading accuracy is lower in less transparent orthographies (e.g., French, Portuguese, Danish) and lowest in the least transparent (opaque) orthography of English (Frith, Wimmer, & Landerl, 1998; Seymour et al., 2003). Therefore, in transparent orthographies, reading speed is a better indicator of reading performance than reading accuracy (e.g. Diamanti et al., 2018; Wimmer, 1993), while in opaque orthographies both reading speed and reading accuracy are good indicators.

Orthography-specific differences in typical reading development are associated with different manifestations of developmental dyslexia. In children with developmental dyslexia, reading accuracy is less impaired in transparent orthographies than in opaque orthographies (e.g., Diamanti et al., 2018; Landerl

et al., 1997). In addition, reading speed is more impaired than reading accuracy in transparent languages. In contrast, both reading accuracy (particularly for low-frequency words and nonwords) and speed are impaired in English children with developmental dyslexia (Landerl et al., 1997). Other cross-orthography studies (e.g., Diamanti et al., 2018) also show that English speaking children with developmental dyslexia are more impaired in reading accuracy, but equally impaired in reading speed, when compared to children who learn more transparent orthographies. Thus, dyslexic reading in opaque orthographies is both slow and less accurate, whereas dyslexic reading in transparent orthographies is slow but mostly accurate.

In the particularly opaque orthography of Chinese, individuals with developmental dyslexia are slow and inaccurate in character recognition/word reading (see McBride et al., 2018). Note, however, that there are large literacy-relevant cultural differences within the Chinese society, such as differences in spoken languages (leading to diglossia with over 200 spoken languages), scripts (traditional vs. simplified), age of onset of education and teaching methods (for overviews, see, McBride, 2016; McBride et al., 2018), which has an impact on literacy acquisition but also on differences in the diagnosis of developmental dyslexia (McBride et al., 2018).

Cultural differences and their impact on the transition from information processing level to skill level

In the following part, we will focus on the impact of cultural factors on the transition from the information processing level to the skill level. In particular, we will focus on how different writing systems and orthographies determine the relative importance of the cognitive functions required for skill acquisition in order to create a literature-specific cognitive procedure. In both cross-sectional and longitudinal studies, cognitive functions (e.g., phonological and morphological awareness, RAN) have been found to be associated with reading across orthographies (see, Landerl et al., 2022, for a review), while their relative importance may differ between them. This is of interest because a given deficit at the information processing level may contribute either more or less to a possible manifestation at the skill level, depending on how significant that particular cognitive precursor function is and when it is recruited in the process of literacy acquisition.

Regarding alphabetic orthographies, research on universality vs. specificity of orthography in typical and impaired reading revealed that the relative impact of precursor cognitive functions on literacy acquisition (e.g., phonological awareness, RAN) depends primarily on the transparency of the orthography (e.g., Landerl et al., 2019; Moll et al., 2014; Ziegler et al., 2010; see Landerl et al., 2022, for a review). For instance, the impact of phonological awareness on reading is stronger in opaque orthographies than in transparent orthographies (Landerl et al., 2013; Moll et al., 2014; Ziegler et al., 2010). Moreover, the correlation of RAN with alphanumeric items and reading speed is stronger in opaque compared to transparent orthographies (see, Araújo et al., 2015, for a review), while this dissociation was not found for RAN with objects (Ziegler et al., 2010). Note, however, the results of studies on orthography-related differences in the correlation between RAN and reading performance are not consistent (Landerl et al., 2022). As we outlined before, longitudinal studies revealed that the relationship between precursor cognitive functions (phonological and morphological awareness, but not RAN) and reading are reciprocal (see Landerl et al., 2022, for an overview). In reading acquisition, children must be able to recognize phonemes and match them to the correct graphemes, but in turn, these precursor cognitive functions also develop with increasing reading experience (see Fig. 1). In contrast, RAN was found to be an unidirectional precursor cognitive function of reading not influenced by reading development (see Landerl et al., 2022, for an overview). Landerl et al. (2022) explain this by the assumption that RAN only indicates the efficiency of forming and retrieving the visual-verbal associations and is not important for understanding how spoken language is represented by written symbols. The former is important in all orthographies, which explains why, in contrast to phonological awareness, only few orthography-related differences in the relevance of RAN for reading are found. Regarding impaired reading acquisition, a meta-analysis of reading-level matched dyslexia studies in transparent alphabetic orthographies (Parrila et al., 2020) revealed deficits of children with

developmental dyslexia compared to reading-level matched controls only in phonological awareness, but not in RAN, phonological memory and auditory temporal processing. Moreover, a meta-analysis of Araújo and Faísca (2019) found no deficits in RAN in children and adults with developmental dyslexia compared to reading-level matched controls, although strong deficits in RAN were found compared to age-matched controls. These, however, were found independent from orthographic transparency and the type of writing system (alphabetic vs. nonalphabetic).

In contrast, a meta-analysis of adult data (Reis et al., 2020) indicates an impact of orthographic transparency on the manifestation of developmental dyslexia. In particular, deficits at both skill level (i.e., reading accuracy, reading speed, reading comprehension, spelling) and information processing level (i.e., phonological awareness, but not RAN) were found to be more severe in intermediate (e.g., German, Swedish) and opaque orthographies (e.g., Danish, English, Hebrew) compared to transparent orthographies (e.g., Finnish, Italian, Polish). Furthermore, the deficits were found to be more severe at skill level compared to information processing level and more severe for speed (in word and pseudoword reading, phonological awareness and orthographic knowledge) compared to accuracy measures.

Regarding the morphosyllabic writing system of Chinese, the pattern of impaired cognitive functions identified in individuals with developmental dyslexia overlaps only partially with that found for the alphabetic writing system. Similar to alphabetic orthographies, Chinese children with reading difficulties showed deficits in various cognitive functions (e.g. phonological awareness, working memory, RAN, morphological awareness, orthographic knowledge, visual and motor abilities) compared to age-matched children (see, Peng et al., 2017, for meta-analysis). However, compared to reading-level matched children, only deficits in RAN and orthographic knowledge (about orthographic regularities) remained. Interestingly, a recent meta-analysis (Georgiou et al., 2021) found no greater deficits in orthographic knowledge in individuals with developmental dyslexia (versus age- or reading level-matched controls) in non-alphabetic relative to alphabetic writing systems. This is surprising, particularly since orthographic knowledge is additionally defined slightly differently in non-alphabetic orthographies such as Chinese (i.e., knowledge of the positions, structuring, and functions of radicals, and children's ability to differentiate real characters and pseudo-characters/visual symbols) compared to alphabetic orthographies. The reason may be that not all studies from non-alphabetic writing systems included in this meta-analysis have been conducted in Chinese. In contrast to alphabetic orthographies, where phoneme awareness is the strongest predictor of reading skills, morphological awareness (as a further language-related cognitive function) has been identified to be the most important predictor of developmental dyslexia in Chinese children, although the predictive power of phonological awareness and RAN was also substantial (Song, Zhang, Shu, Su, & McBride, 2020). Morphological awareness, i.e. the ability to manipulate morphemes while applying word formation rules in a given language, is considered particularly relevant in opaque orthographies (morpho-syllabic Chinese and alphabetic English) because morphology is needed to determine word pronunciation (see Landerl et al., 2022).

The relative importance of the cognitive functions involved in successful literacy acquisition is determined by the specific requirements of a writing system. The importance of orthographic knowledge and morphological awareness for skilled and impaired reading in Chinese compared to reading in alphabetic (especially in transparent) orthographies is greater because readers have to focus on larger orthographic units in Chinese as phoneme-level grain size is not available (or at best very inconsistent) in this writing system (see the "Psycholinguistic grain size theory" Goswami, 2010; Ziegler & Goswami, 2005). At the same time the importance of phonological awareness for Chinese reading is smaller because the Chinese orthography, unlike alphabetic orthographies, does not correspond to the segmental structure of the language. Furthermore, only 39% of the Chinese characters taught in school are regular and contain reliable information about their pronunciation (Shu et al., 2003). Hirshorn and Harris (2022) speak of an orthographic-dependent tradeoff in the use of phonological/phonemic and morphological/semantic processing to enable skilled reading with an attentional focus on different sized orthographic units resulting from the nature of the writing system (small units such as phonemes in alphabets vs. larger units such as

syllables in syllabaries and morphemes in logosyllabaries or morphosyllabaries).

Non-linguistic abilities (e.g., visual and copying abilities) also appear to play a role in reading acquisition in writing systems with greater visuospatial grapheme complexity. Reading complex graphemes, like in Chinese, requires detailed visual discrimination to distinguish between complex characters which are unique but very similar. Thus, initial reading acquisition in Chinese can be predicted by visuo-orthographic abilities (e.g., Siok & Fletcher, 2001) and basic visual processing abilities (e.g., Luo et al., 2013). However, there is also evidence for an inverse effect of reading acquisition on visual abilities indicating a bidirectional relationship (McBride-Chang et al., 2005, 2011c). In a cross-orthography study of McBride-Chang et al. (2011c), Chinese and Korean children (both learning complex characters) outperformed Israeli and Spanish beginning readers of alphabetic orthographies with simple graphemes in a visual task. Furthermore, in all orthographies (except Korean), skilled readers performed better on the visual task than less proficient readers, emphasizing the important role of literacy proficiency in the development of visuospatial abilities (see also Eviatar & Huettig, 2021; Fernandes, Arunkumar, & Huettig, 2021; Fernandes & Kolinsky, 2016; Pegado et al., 2014). Importantly, in a second, one-year longitudinal study, the authors could find a substantial effect of earlier reading proficiency on visuospatial abilities, which was greater than the inverse effect of visual skills on reading performance.

The relevance of non-linguistic skills (copying skills, handwriting practice and handwriting quality) to literacy acquisition in writing systems with more complex graphemes also seems to be due to the way in which these more complex characters are learned. In Chinese societies, the most common teaching method for literacy acquisition is copying Chinese characters (Wang et al., 2014). Copying abilities of Chinese children were found to be correlated to reading and writing of words in Chinese (McBride-Chang et al., 2011a). Moreover, copying abilities could discriminate between children with and without developmental dyslexia. Crucially, this discrimination on the basis of copying abilities was shown only in Chinese, but not in English (Kalindi et al., 2015), again indicating cultural influences.

Similar to the findings from alphabetic orthographies (and even within the Chinese orthography), there is a high variability of deficits in cognitive functions identified in Chinese children with developmental dyslexia (e.g., Song et al., 2020). For instance, in the study by Song et al. (2020), different deficit groups of Chinese children with developmental dyslexia could be found: a phonological deficit group, a RAN deficit group, a morphological deficit group, and a global deficit group with impairments in all these functions. Crucially, deficits in the various cognitive functions can be used to validate a diagnosis of developmental dyslexia (Pennington et al., 2012; see Lachmann et al., 2022, for further information regarding the diagnoses of developmental dyslexia), and could provide additional indications for intervention.

Conclusions

Developmental dyslexia is a neurodevelopmental disorder characterized by an unexpected impairment in literacy acquisition leading to specific poor academic achievement and possible secondary symptoms. The criterion of unexpectedness is determined on the basis of a criterion-based individual deviance in literacy skill performance compared to an age reference population having the same adequate environmental conditions. Cultural influences are thus practically excluded from the diagnosis of developmental dyslexia. On the other hand, there is a large body of work on cultural influences (e.g., of the writing system and the specific orthography) on developmental dyslexia, which we have reviewed in the present paper. The multiple-level framework of developmental dyslexia introduced here considers the possible influence of these excluded factors by defining five levels where the causal pathway, upon which a given genotype is (1) expressed and (2) hierarchically transmitted from one level to the next, is influenced by individual and environmental factors moderated by culture. Various risk and protective factors may moderate the transitions from one level to the next and, thus, the likelihood of exhibiting developmental dyslexia. Within the multiple-level framework, different findings on the relative importance of different cognitive precursor functions (information processing level) for reading acquisition and developmental dyslexia (skill level) across different orthographies

can be explained by considering the different demands on the reading process/literacy-specific cognitive procedures imposed by the specifics of the writing systems and orthographies.

We do not want to neglect the fact that there are many commonalities in typical and impaired reading acquisition across orthographies and writing systems (see Verhoeven & Perfetti, 2022). However, we argue that the differences between writing systems and the specificities of each orthography should at least be considered. This could be particularly important in prevention and intervention, which should be considered in more detail in future research.

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