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A Taxometric Investigation of Developmental Dyslexia Subtypes

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Long-standing issues with the conceptualization, identification and subtyping of developmental dyslexia persist. This study takes an alternative approach to examine the heterogeneity of developmental dyslexia using taxometric classification techniques. These methods were used with a large sample of 671 children ages 6–8 who were diagnosed with severe reading disorders. Latent characteristics of the sample are assessed in regard to posited subtypes with phonological deficits and naming speed deficits, thus extending prior work by addressing whether these deficits embody separate classes of individuals. Findings support separate taxa of dyslexia with and without phonological deficits. Different latent structure for naming speed deficits was found depending on the definitional criterion used to define dyslexia. Non-phonologically based forms of dyslexia showed particular difficulty with naming speed and reading fluency. Copyright © 2012 John Wiley & Sons, Ltd.

Practitioner Points:

- Support for separate subtypes of dyslexia, with and without phonological deficits (PDs), indicates a need for different approaches to intervention.
- A discrepancy-based criterion identifies more non-PD cases that may be missed with a response-to-intervention diagnosis.
- Sound symbol correspondence and decoding measures may best distinguish cases of dyslexia with and without PDs.

Keywords: developmental dyslexia; subtypes; double deficit hypothesis; taxometric analysis

Developmental dyslexia has been the focus of a century of research across multiple fields (e.g., Orton, 1928; Geschwind & Behan, 1982; Shaywitz *et al.*, 1992; Fletcher, 2009). Along this course, dispute regarding dyslexia's aetiology, definition, identification and even its existence has persisted. But one historical trend in any conceptualization of dyslexia is the recurrent view that the 'syndrome' is composed of separate syndromes, usually referred to as subtypes. Within this perspective, delineating subtypes is key to establishing both the aetiology and diagnosis of developmental dyslexia.

Research efforts in the past few decades have led to great gains in reconceptualizing developmental dyslexia as a neurodevelopmental syndrome (Pennington, 2009), and this process has contributed to improved approaches to remediation. The most recently conceived defining characteristics are more inclusionary than in the past, including specific difficulties in word reading linked to phonological processing (Lyon, Shaywitz, & Shaywitz, 2003). Although it is widely held that dyslexia is a heterogeneous disorder, the prevailing

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view is that phonological deficits (PDs) are a primary and common cause. Currently, there is controversy over the classification scheme whereby PDs and naming speed deficits (NSDs) constitute different subtypes (e.g. Vukovic & Siegel, 2006; Vaessen, Gerretsen, & Blomert, 2009). Although evidence shows that these factors independently predict reading and characterize different groups of individuals, there are statistical concerns with categorizing individuals using continuous predictors that are correlated (Compton, DeFries, & Olson, 2001; Schatschneider, Carlson, Francis *et al.*, 2002). Contributing to the disparate findings are differences across studies with regard to cutoff scores used to identify subgroups and sample variations in size and reader types (i.e. typical developing vs. reading disabled).

The goal of the present study is to investigate the power of taxometric analysis to shed increasing light on the most prominent behavioural symptoms in models of dyslexia (e.g. phonological weaknesses, naming speed/fluency deficits). Taxometric analysis, developed by Paul Meehl and his colleagues (Meehl & Yonce, 1994, 1996; Waller & Meehl, 1998), includes a powerful set of classification techniques that aims to identify the latent structure of psychological constructs. We base the present analysis on the theoretical model proposed by Wolf and Bowers (1999), the double deficit hypothesis (DDH), because 'categories within a classification system will proliferate unless bounded by theory' (Schmidt, Kotov, & Joiner, 2004, p. 25). Thus theoretically based classifications contribute to the development of diagnostic parsimony and differential treatments.

The Double Deficit Hypothesis

The double deficit hypothesis (Wolf & Bowers, 1999) is a model-driven approach to subtyping developmental dyslexia, which asserts that individuals with phonologically based deficits and/or NSDs constitute separate classes of dyslexic readers. Within the model, four subtypes are classified according to the presence or absence of PDs and NSDs, with the most impaired subtype exhibiting both deficits, and the smallest subtype characterized by neither. Readers within the PD subtype are characterized by marked difficulty decoding words and exhibit little phoneme awareness of the sound structure of words. Such individuals have special difficulties with pseudo-word reading, grapheme–phoneme correspondence and with tasks that require them to blend phonemes into words or to pronounce parts of words by removing one or more phonemes. Readers within the second, naming speed/fluency-deficit subtype are markedly slower at naming a sequence of serially presented visual stimuli, such as letters or numbers or objects. This deficit is believed to be an index of automatic or rapid processing within one or more of the components necessary for the development of fluent reading and ultimately comprehension.

The contribution of phonological skills to reading acquisition is firmly established (Goswami & Bryant, 1990; Bradley & Bryant, 1983; Bruck, 1992; Rack, Snowling, & Olson, 1992), and the causal role of these deficits in decoding failure has been one of the most consensually agreed upon tenets of dyslexia research (Lyon *et al.*, 2003; Snowling, 2001; Morris *et al.*, 1998; Shankweiler *et al.*, 1995; Fletcher *et al.*, 1994). Many theorists assert that naming speed is simply another phonological skill (e.g. Wagner & Torgesen, 1987; Vukovic & Siegel, 2006); however, reading intervention programs focused solely on phonological skills training often fail to produce gains in reading fluency and comprehension for a number of individuals diagnosed with dyslexia (Torgesen, 2000; Blachman, 1997; Vellutino *et al.*, 1996). Also, several lines of evidence support the independence of NSDs and PDs, including statistical, cross-linguistic and brain imaging investigations.

Many studies demonstrate that phonological and naming speed skills are statistically independent of one another (Blachman, 1984; Mann, 1984; Felton & Brown, 1991; Boada & Pennington, 2006) and independently predict later reading ability (Wolf & Bowers, 1999, 2000) and different aspects of reading (Bowers, 1995; Schatschneider, Fletcher, Francis *et al.*, 2004; Savage & Frederickson, 2005; Pennington, Cardoso-Martins, Green, & Lefly, 2001). Further, dyslexic readers show more pronounced deficits on naming speed than on phonological skills measures in more transparent languages, including German, Finnish, Dutch and Spanish (Wimmer, 1993; Wimmer, Mayringer, & Landerl, 2000; Yap & van der Leij, 1993; Wolf, Pfeil, Lotz, & Biddle, 1994; Holopainen, Ahonen, & Lyytinen, 2001; van den Bos, 1998; Escribano, 2007), and in languages with entirely different orthographies, such as Hebrew, Chinese and Japanese (Breznitz & Berman, 2003; Ho, Chan, Tsang, & Lee, 2002; Ho, Chan, Lee *et al.*, 2004; Tan, Spinks, Eden *et al.*, 2005; Kobayash, Haynes, Macaruso *et al.*, 2005). This set of cross-linguistic results shows naming speed is a stronger diagnostic indicator and predictor of reading performance in orthographies, which demand less phonological analysis. Finally, neuroimaging studies reveal how processes recruited by phonology and rapid naming are subserved by different areas of the brain (Misra, Katzir, Wolf, & Poldrack, 2004). In poor and dyslexic readers, rapid naming is correlated with grey and white matter structural anomalies that are unrelated to phonological performance (Eckert *et al.*, 2003; Deutsch *et al.*, 2005). The imaging findings demonstrate different sources of potential breakdown in the neural reading network used by individuals with dyslexia.

Taken together, these lines of evidence provide support for independent PDs and NSDs in dyslexia. However, there are inconsistencies in the literature that call into question this conclusion. For example, Pennington *et al.* (2001) found limited evidence for NSDs that were independent of PDs in dyslexic children and a weaker contribution of naming speed to reading. Schatschneider *et al.* (2002) and Chiappe, Stringer, Siegel, & Stanovich (2002) found that the shared variance of phonological and naming speed measures was as predictive as the unique variance of each predictor. To resolve these issues, we took a different approach to test the assertions of the DDH subtyping scheme at the latent structural level using Meehl's (1995) taxometric procedures with a large group of children identified as having severe reading disorders.

Taxometrics

Because model-driven subtyping schemes often entail 'open concepts'—having 'fuzzy boundaries, an absence of defining indicators and an unknown inner nature (such as unknown etiology)' (Schmidt *et al.*, 2004, p. 5), we aimed to measure the latent structure of the DDH subtypes with taxometric procedures (Meehl & Yonce, 1994, 1996; Waller & Meehl, 1998). The goal of taxometric analysis is to 'arrange entities into natural categories' (Schmidt *et al.*, 2004, p. 7), or, in the words of Plato, to 'carve nature at its joints' (*Phaedrus*, 265d-266a). The taxometric procedures are necessary to identify latent classes or subtypes because even if distributions are not bimodal, they can still contain two distinct subgroups (those with and those without deficits). As Meehl (1995) described, we commonly confuse continuity in the behavioural measure (i.e. scores) with continuity of individual people. Taxometric procedures aim 'at the inferred state (whether genetic, psychodynamic or biochemical) rather than the symptomatically dispersed forms of the symptoms' (Meehl & Yonce, 1994, p. 1063).

We chose taxometric procedures over other methods of classification because other statistical methods, like cluster analysis and latent growth analysis, form groupings that

maximize between-group variance, and thus will always yield subgroups regardless of whether groupings are more dimensional than taxonic. These methods can be considered to impose rather than seek structure in the data (Beauchaine, 2003). Taxometric procedures, on the other hand, can be used to ask the discrete question of whether subgroups are present or not. Importantly, this set of procedures offers strong support for the construct validity of subtypes and can thus contribute to developing different intervention strategies across taxa.

Reviews of the taxometric approach are available elsewhere (see Meehl, 1995; Beauchaine, 2003; Schmidt *et al.*, 2004; Ruscio, Haslam, & Ruscio, 2006), so we provide only a brief overview here. Meehl's (1995) taxometric procedures are described as 'coherent cut kinetics' (p. 269) that use multiple indicators of a latent trait (X, Y, Z). One indicator (such as phonemic awareness scores) is 'cut' into small ranges of scores, and people are divided into sets based on how they scored on that indicator. The procedures are based on the phenomenon that the relative proportion of latent classes changes across the dimension of an indicator variable (X). At each extreme on the indicator dimension (i.e. very low scores and very high scores), most individuals will belong to one of two classes (e.g. a deficit taxon and a non-deficit group). At a certain point (the 'Hitmax Point'), where there is the greatest admixture of the two classes, covariation of other indicator variables (Y, Z) will be greatest. Thus, if the covariance (or another summary statistic) of indicators Y and Z changes along cuts from low to high scores of the X indicator variable, then one can infer the presence of a taxon (Meehl & Yonce, 1996, p. 1092). This is typically seen as an inverted U when plotted.

Our approach differs from previous investigations of the DDH subtypes in that it does not employ regression techniques, which must address the covariation of the predictor variables, nor does it form independent categories of individuals based on single predictor measures, which must address the issue of cutpoints to distinguish categories. We specifically addressed two questions related to the DDH model separately:

(1) Are all children with severe reading disorders the same with regard to having PD?; and
(2) Are naming speed deficits a separate characteristic from PDs that contribute to different forms of reading disability?

In addition, we assessed these two questions within two subsamples that included

- children who met a discrepancy definition of dyslexia and
- children who met a low-achievement definition.

The answers to these questions are significant because they imply the need for reading interventions that differ either in intensity or in approach.

METHOD

Participants

Six hundred and seventy-one children identified to take part in a multi-site intervention study of reading disabilities over a 10 year period were included in the present study. The children ranged in age from 6-6 to 8-6 and were enrolled between first and third grade in schools. Each child was identified as having a reading disability with screening measures

that included Woodcock Reading Mastery (WRMT-R, Woodcock, 1998) word identification, word attack and passage comprehension tests, the Wide Range Achievement (Wilkinson, 1993) Reading test and the Kaufmann Brief Intelligence test (Kaufman & Kaufman, 1990). Each individual met either a low-achievement criterion and/or a discrepancy criterion for reading disability. The low-achievement criterion consisted of a standard score below 85 (i.e. $<$1 SD) on either the WRMT-R Basic Skills or Total Reading cluster, or on a composite score of WRMT-R word identification, word attack, passage comprehension and WRAT-R reading. The discrepancy criterion was determined as a difference of greater than 1 standard deviation between ability-predicted achievement (based on Kaufmann Brief Intelligence test full-scale IQ) and any one of these three reading cluster scores. All participants were primary English speakers with no history of primary sensory or neurologic disorders. None had repeated a grade and thus were at their age-appropriate grade level at the time of entering the study.

Measures

Indicator variables were selected mainly for their content validity and also with consideration of discriminant validity. Validity recommendations set by Meehl (1995) included low 'nuisance' correlations between the indicators that are approximately equal within the groups and significant separation on indicators between groups.

Phonological processing deficits in children with dyslexia entail problems with phoneme awareness, learning grapheme–phoneme correspondence rules and decoding (Stanovich & Siegel, 1994). Indicators for a phonological processing-deficit taxon included these three facets of deficits. Phoneme awareness was indexed with the Elision and Nonword Repetition subtests of the Comprehensive Test of Phonological Processing (CTOPP, Wagner, Torgesen, & Rashotte, 1999). Phoneme-to-grapheme correspondence was measured with the Sound Symbol Conversion Test (Lovett *et al.*, 1994). Decoding was assessed with the phonemic decoding subtest of the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). Because first graders are not expected to achieve the same level on these tests as second or third graders, raw scores were converted into standardized units where available. Scale scores were used for the CTOPP measures, standardized scores were used for the TOWRE measure and total per cent correct on all lists was used for the Sound Symbol test. These measures were entered into the analyses as indicators of a PD taxon.

Facets of an NSD taxon were considered to include difficulty with rapid naming of visually presented symbols and with processing speed. Serial naming was assessed with the Rapid Automatized Naming (RAN) test (Denckla & Rudel, 1974; Wolf & Denckla, 2005) for letters and for objects. Processing speed was measured with the Coding subtest of the Wechsler Intelligence Scales for Children (Wechsler, 1991). Standard scores for the RAN measures and scale scores for the Coding subtest were entered into the analyses as indicators of an NSD taxon.

Other measures of reading were examined for potential differences between taxa. It is noted that reading fluency measures are more closely related to NSDs, whereas reading accuracy measures are related to PDs (Bowers, 1995). In addition, naming speed has been related to spelling (Savage, Pillay, & Melidona, 2008). Therefore, differences between taxa on measures of reading fluency, comprehension and spelling were of interest, in addition to reading-related measures of vocabulary and listening comprehension. Measures of these skills included fluency measures for words (TOWRE sight word subtest) and text passages (Gray Oral Reading Test (GORT); Wiederholt & Bryant, 1992), comprehension measures

for oral (GORT oral reading quotient) and silent reading (WRMT-R passage comprehension subtest) and for listening (Wechsler Individual Achievement Test II, listening comprehension; Wechsler, 2001). Also, spelling (Peabody Individual Achievement Test; Markwardt, 1989) and vocabulary (Peabody Picture Vocabulary Test; Dunn & Dunn, 1997) scores were examined.

Procedure

Three separate taxometric procedures were used, MAMBAC, MAXEIG and L-Mode (see Meehl & Yonce, 1994; Meehl, 1995; Ruscio *et al.*, 2006) with the multiple indicators alternated as the X-variable along which the 'cuts' were made. The three procedures were run for each of the research questions as a means of a consistency check.

We tested two specific hypotheses separately: first, for the presence of a PD taxon, and second for the presence of an NSD taxon. Separate hypotheses were tested because those individuals with both PDs and NSDs (the 'double deficit', (DD) group) will be contained in the taxon studied and not in the complement group. So, for example, when testing for a PD taxon, both PD and DD individuals would make up the taxon group, and the complement group would presumably include those with single NSDs. Conversely, in testing for an NSD taxon, the DD individuals would be included with the NSD individuals to make up the taxon group, and individuals with a single PD would make up the complement group. Thus, Hypothesis 1 tests for separate taxa in disabled readers with and without PDs and Hypothesis 2 tests for separate taxa with and without NSDs, following Wolf and Bowers's (1999) model.

RESULTS

All analyses were run using algorithms provided by Ruscio (2011). For all procedures, at each cutpoint along the dimension of one indicator (or factor score for L-Mode), the summary statistic is calculated (i.e. difference in means above and below the cut for MAMBAC, eigenvalues for MAXEIG, and density for L-Mode), then plotted across the *x*-axis to produce the taxometric curve. Fifty cuts were used with the MAMBAC and MAXEIG procedures, with five replications of the analysis to control for the arbitrary selection of equal scoring cases to adjacent windows, and with overlap between windows (90% of the subsample) for MAXEIG as a means of smoothing the data. For each hypothesis, the taxon base rate was first estimated with MAXEIG, and this estimate was entered into each of the procedures to generate empirical comparison data, as described next.

The shapes of taxometric curves indicate the presence of a taxon. Thus, we primarily used curve fit indices developed by Ruscio (2011) to quantify whether the data curves had a more taxonic or dimensional structure. Empirical sampling distributions for taxonic and dimensional comparison data were generated with a bootstrap procedure (Efron & Tibshirani, 1993), allowing for comparison of the results with simulated taxonic and dimensional curves based on the sample parameters.[1] A comparison curve fit index (CCFI) was then calculated to compare the research results with the simulated data distributions to allow for a quantifiable assessment of the taxonic or dimensional nature of the results based on the graphical output of the research and simulated data. This index is based on a ratio of the average root mean square residuals of *y*-values for the research data compared with the simulated data. Accordingly, a CCFI above 0.50 would indicate a

taxonic data set, and a CCFI below 0.50 would indicate a dimensional data set. Following Ruscio, Walters, Marcus, & Kaczetow (2010), a conservative test of CCFI ($<$0.40 or $>$0.60) yielded highly accurate rates (99.9%) for identifying data as dimensional or taxonic, respectively, and less conservative thresholds yielded similarly high accuracy (for CCFI $<$0.45 or $>$0.55, accuracy = 99.4%, and for CCFI $<$0.50 or $>$0.50 accuracy = 98%). Mean base rate estimates are also reported for the MAMBAC and MAXEIG taxometric analyses. In addition, between-group validity (Cohen's *d*) was estimated for each indicator using MAXEIG's group classification procedure.

Results are presented for each sample (whole sample, discrepancy-based subsample, and low-achievement subsample), with the two hypotheses (PD taxon and NSD taxon) tested separately using each of the three taxometric procedures (MAMBAC, MAXEIG and L-MODE).

Whole Sample

Hypothesis 1: Testing for a PD Taxon

Four indicators were entered into the analyses: CTOPP Elision and Nonword Repetition, Sound Symbol Conversion, and TOWRE Phonemic Decoding scores. There were complete data on all four measures for 617 of the children identified with dyslexia.

- MAMBAC procedure.

All pairwise combinations of the four indicators were used wherein each indicator served as either an input or output variable, yielding 12 MAMBAC curves. The averaged curve is shown in Figure 1 (top row, dark line with points), superimposed on simulated data with taxonic structure (top row, left plot) and with dimensional structure (top row, right plot).

As seen in the figure, the average of the MAMBAC curves shows a shape that is more consistent with the empirically derived taxonic comparison curves than the dimensional comparison curves. The curve fit index supports this conclusion (CCFI = 0.60). The MAMBAC analysis also indicated a mean base rate across curves of 0.62.

- MAXEIG procedure.

Each indicator served as the input variable for one curve, with all other variables combined to calculate eigenvalues across the dimension of the input variable. Thus, four MAXEIG curves were generated.

As seen in Figure 1 (middle row), the average research data curve (dark line with points) followed the shape of the empirically derived taxonic comparison data (left plot). The curve fit index indicates that the research sample is taxonic (CCFI = 0.77). The MAXEIG analysis also indicated a mean base rate across curves of 0.47.

The MAXEIG procedure also allows for classification of each individual into taxon or complement groups. Classification using MAXEIG Hitmax showed a degree of concordance with the traditional method of DDH subtyping.[2] In Figure 2A, the DDH subtypes are collapsed into phonological (PD plus DD) and non-phonological based subtypes (NSD and others). As can be seen, a good proportion of the non-phonological DDH types fall into the complement group (80%), whereas many of the phonological DDH types fall into the taxon (66%) ($\Phi = 0.48$, $p < .001$). Figure 2B shows how the three DDH subtypes are distributed across the MAXEIG taxon and complement groups. As

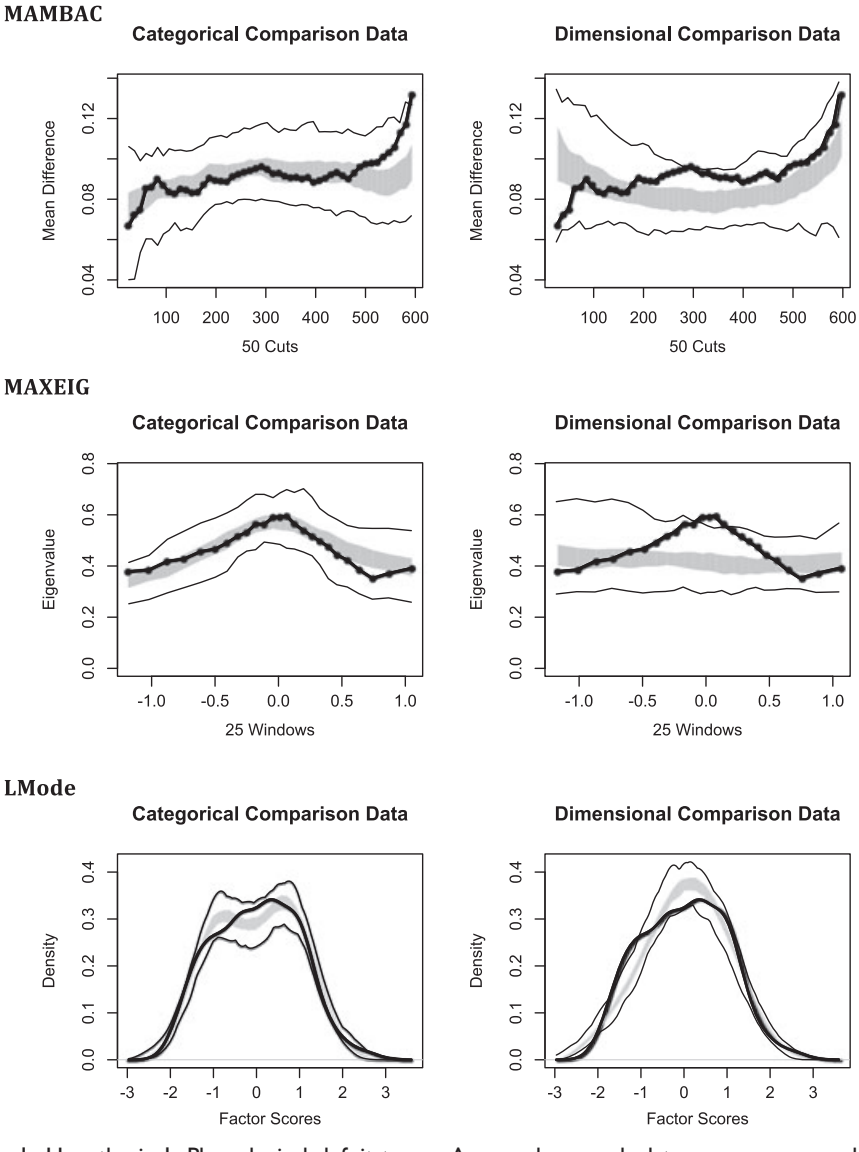

Figure 1. Hypothesis 1: Phonological deficit taxon. Averaged research data curves compared with simulated taxonic and dimensional data curves (bootstrapped) for three taxometric procedures (MAMBAC, MAXEIG, L-Mode). Each plot presents change of the summary statistic (*y*-axis) across successive cuts of the indicator variable (*x*-axis). Research data (dark lines with points) are superimposed on empirical sampling distributions for taxonic data (left plots) and dimensional data (right plots). Light bands indicate minimum and maximum empirical values, and grey bands indicate the middle 50% of the empirical values. Research curves that follow the shape of the categorical comparison data (grey bands) indicate taxonic structure.

shown, the subtypes fall into the expected taxon and complement groups a good portion of the time ($\Phi = 0.50$, $p < .001$). This is mostly true for the DD subtype, 74% of which falls under the PD taxon, and the NSD subtype, 72% of which falls under the non-PD complement group. In the single PD subtype, 65% of these cases were classified into the PD taxon. The 'other' category for the DDH criteria was split primarily into the non-PD complement group.

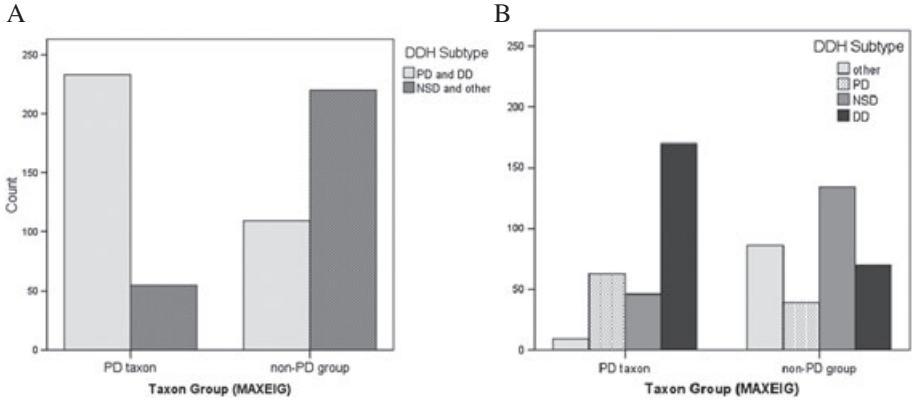

Figure 2. Proportions of double deficit (DD) subtypes within taxon groups. [A] Number of individuals across double deficit hypothesis (DDH) subtypes with and without phonological deficits represented within each of the taxon groups (PD, non-PD). [B] Number of individuals across four DDH subtypes (DD, naming speed deficit (NSD), PD and other) represented within each of the taxon groups (PD, non-PD). Taxon groups were determined with the MAXEIG Hitmax procedure.

- L-Mode procedure.

Each possible triplet of indicators was run, yielding four curves based on the factor analysis of each set of indicators (Figure 3). Two of these, plots B and C, show data curves with two modes that are more consistent with the simulated taxonic curve ($CCFI_{(B)} = 0.63$, $CCFI_{(C)} = 0.64$). Plots A and D do not show a bimodal shape and do not conform more closely to either the taxonic or dimensional simulated curves ($CCFI_{(A)} = 0.44$, $CCFI_{(D)} = 0.50$). The CCFI for the analysis with all four indicators was 0.56 (Figure 1, bottom row).

Summary of Taxometric Analysis for Hypothesis 1

Evidence of a taxonic structure was found for Hypothesis 1, testing for independent groups of dyslexic readers with and without PDs. Across three different taxometric procedures yielding multiple curves, many supported a taxonic shape to the data (i.e. peaked curve). Further, comparison with empirically derived curves having taxonic and dimensional structure indicated that there is a taxonic structure to the research data (Figure 1). The MAMBAC and MAXEIG analyses and two of the four L-Mode analyses yielded consistency of a taxonic solution, showing a strong degree of consistency across the procedures. In addition to consistency, the mean of the CCFI values is shown to achieve high levels of accuracy for identifying taxonic versus dimensional outcomes (Ruscio *et al.*, 2010). Here, the mean CCFI across these three procedures was 0.64 (Table 1), which exceeds the more conservative threshold of CCFI values (Ruscio *et al.*, 2010). Of note, the L-Mode procedure differs from the others in that it does not follow the same coherent cut kinetics approach using sliding cuts along the dimension of an indicator. Instead, factor score distributions are used to search for latent modes in determining taxonic structure (Ruscio *et al.*, 2006, p. 117). The two plots revealing taxonic bimodality both included the sound symbol and phonemic decoding measures in the factor scores. It may be that these two subtests together are particularly relevant components of a latent PD taxon.

The base rate estimates for the research data indicate that between 47% and 62% (with an average 55%) of the dyslexic sample have phonological skills deficits. This estimated

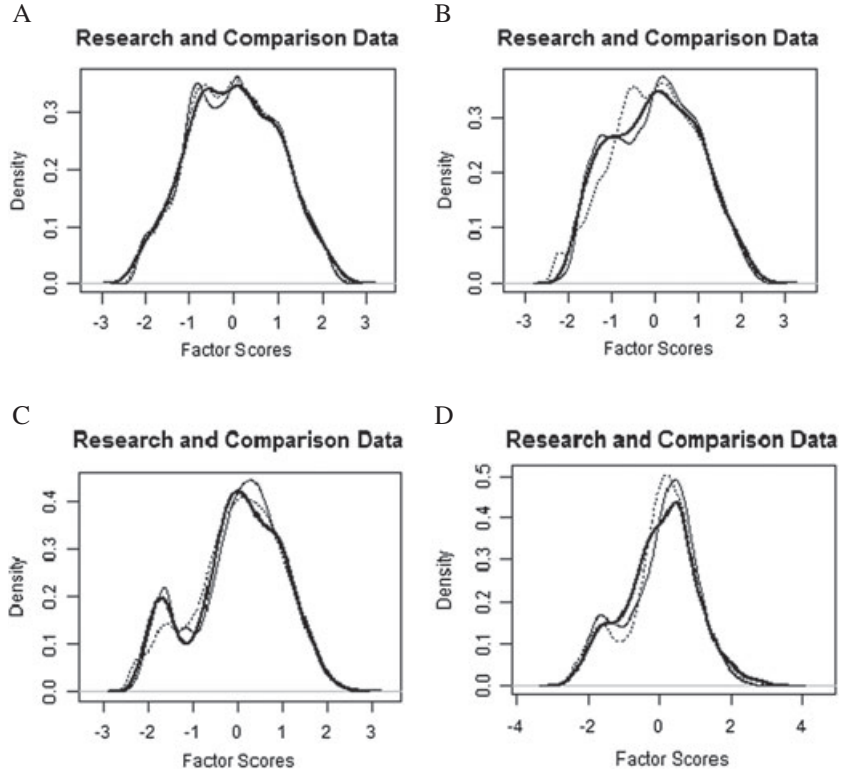

Figure 3. L-Mode curves for Hypothesis 1. Factor scores estimated from sets of indicators: [A] Elision, sound symbol, nonword repetition; [B] Elision, Sound Symbol, Phonemic Decoding; [C] Sound Symbol, Nonword Repetition, Phonemic Decoding; and [D] Elision, Nonword Repetition, Phonemic Decoding. Each curve shows the research data (dark line), superimposed with the empirically simulated taxonic curve (thin line) and dimensional curve (dotted line).

proportion of PD types is somewhat lower than that found in previous subtyping studies. For example, Lovett (1995) found that 76% of her sample was phonological or double deficit types, and Katzir, Kim, Wolf *et al.* (2008) found a 72% rate. However, the average base rate estimate is very close to the proportion of traditionally defined[3] DDH PD types in this sample, which was 58%. An examination of the individuals classified into the taxon group (from the MAXEIG Hitmax procedure) revealed that most were the PD/DD

Table 1. Summary of mean comparison curve fit index values across subsamples for Hypothesis 1 and Hypothesis 2

Hypothesis tested	Whole sample	Discrepancy criterion subsample	Low-achievement-criterion subsample
	M	*M*	*M*
Hypothesis 1 Phonological deficit taxon	0.64	0.64	0.71
Hypothesis 2 Naming speed deficit taxon	0.54	0.43	0.61

subtypes (Figure 2). The two classification methods (MAXEIG hitmax and traditional DDH) were not perfectly related, though, and about one-third of the PD/DD cases were classified into the non-PD complement group. In this case, the MAXEIG classification procedure had a sensitivity value of 0.68 (i.e. the proportion of 'true positive' cases in the taxon group who were PD/DD subtypes) and a specificity value of 0.80 (i.e. the proportion of 'true negative' cases in the complement group who were not PD/DD subtypes).

Hypothesis 2: Testing for an NSD Taxon

Three indicators were entered into each taxometric analysis: RAN letters, RAN objects, and Coding standard scores. There were complete data on all measures for 671 children diagnosed with dyslexia.

- MAMBAC procedure.

All pairwise combinations of the three indicators yielded six MAMBAC curves. The averaged curve is shown in Figure 4 (top row, dark line with points), superimposed on simulated data with taxonic and dimensional structure (top row, left and right plots, respectively). As shown, the average of the MAMBAC curves follows a shape that is more consistent with the empirically derived taxonic comparison curves than the dimensional comparison curves. The curve fit index supports this conclusion (CCFI = 0.63). The MAMBAC analysis also indicated a mean base rate across curves of 0.44.

- MAXEIG procedure.

Each indicator served as the input variable for one curve, generating three MAXEIG curves. The average curve is shown in Figure 4 (middle row). It appears that the research data have a shape that is more consistent with the empirically derived taxonic comparison curves (middle row, left plot) than the dimensional comparison curves (middle row, right plot), although the curve fit index (CCFI = 0.53) does not exceed the more conservative threshold of CCFI values (Ruscio *et al.*, 2010). The MAXEIG analysis also indicated a mean base rate across curves of 0.19.

- L-Mode procedure.

The research data curve is shown in Figure 4 (bottom row, dark line) superimposed on comparison taxonic and dimensional simulated curves. The data do not show two modes, as would be expected with taxonic structure. In fact, the data curve is more closely aligned with the simulated dimensional data (right plot) than the taxonic data (left plot), as is reflected in the curve fit index (CCFI = 0.46).

Summary of Taxometric Analysis for Hypothesis 2

Results for Hypothesis 2, testing for an NSD taxon, were less clear than the results for the first hypothesis. Although the MAMBAC procedure yielded support for a taxonic solution, the MAXEIG and L-Mode procedures did not. Thus, the findings were not consistent (Figure 4). The mean CCFI across these three procedures was also ambiguous (CCFI = 0.54; Table 1). The range of base rates estimated for the research data indicated that between 19% and 44% of this dyslexic sample have naming speed deficits (NSD and DD). These rates are much lower than those found in previous studies (e.g. Lovett, 1995; Katzir *et al.*, 2008). It should be noted, however, that the previous prevalence rates result from rationally derived

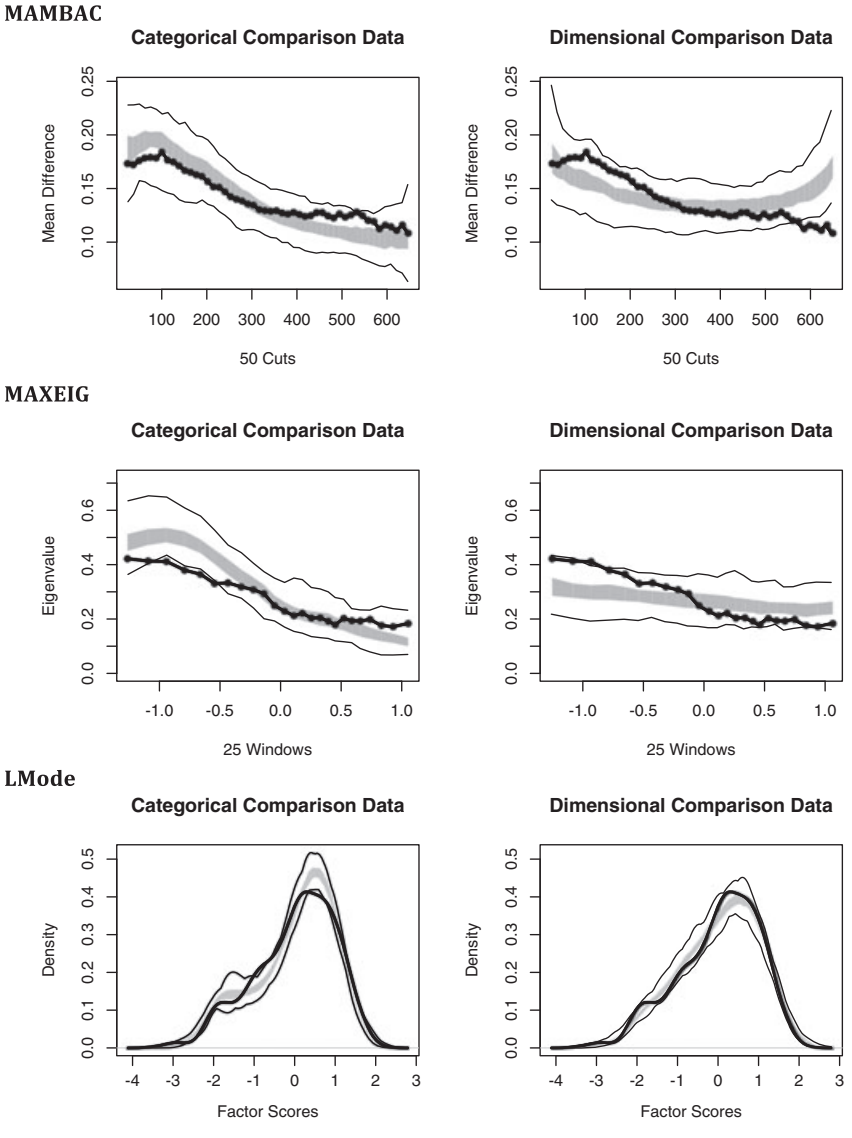

Figure 4. Hypothesis 2: Naming speed deficit taxon. Averaged research data curves compared with taxonic simulated data and dimensional simulated data curves (bootstrapped) for three taxometric procedures (MAMBAC, MAXEIG, L-Mode). Research data (dark lines with points) are superimposed on empirical sampling distributions for taxonic data (left plots) and dimensional data (right plots). Light bands indicate minimum and maximum empirical values, and grey bands indicate the middle 50% of the empirical values. Research curves that follow the shape of the categorical comparison data (grey bands) indicate taxonic structure.

cutoff scores of one standard deviation below the mean, and that an alternate cutoff would have led to different subgroup rates observed in those studies.

Subsample Analyses

The definitional issue of how to identify individuals with dyslexia has undergone much debate in the past, and more recently a change in criteria. A consistent aspect of defining

dyslexia has been the unexpected nature of the reading difficulty. Clearly, it is a tricky matter to operationalize something as unexpected. One may expect reading problems to result from inadequate instruction, for example, but then one needs to define what constitutes adequate instruction. Traditionally, reading problems were considered unexpected if they could not be explained by broad cognitive deficits. Accordingly, the discrepancy model was used to identify cases where reading achievement was significantly below what was predicted by cognitive ability, as measured with IQ. Although this approach follows logic, practical and ethical concerns have led to a shift away from the discrepancy criterion. First, there are issues with the precision of measuring intelligence,[4] and second, this approach essentially meant waiting for children to fail before identifying the problem.

A pertinent question is whether defining dyslexia as simply low reading achievement (i.e. 'garden-variety' poor readers) or with a discrepancy criterion identifies different types of struggling readers. Recently, Reynolds and Shaywitz (2009) questioned the exclusive use of achievement-based criteria, suggesting that the removal of cognitive testing would cause some dyslexic children to be overlooked. For example, several studies have shown that in dyslexic groups identified with a discrepancy criterion, there are different patterns of association between RAN and word reading (Wolf & Obregon, 1992; Ackerman & Dykman, 1993; Biddle, 1996; Badian, 1994) and different proportions of DDH subtypes (Katzir *et al.*, 2008) compared with low-achieving groups. Also, the MAXEIG classification procedure used above for Hypothesis 1 showed a difference in the proportion of discrepancy-defined dyslexia cases between the PD-taxon and the non-PD complement groups. As shown in Figure 5, there is only a small portion of children who meet the discrepancy-only criterion in the PD taxon (middle dark bar), compared with the proportion of these cases in the non-PD group (middle light bar). Therefore, subsequent taxometric analyses were run first with a subset from the present sample of children who met the discrepancy criterion of dyslexia and second with a subset who met the low-achievement definition.

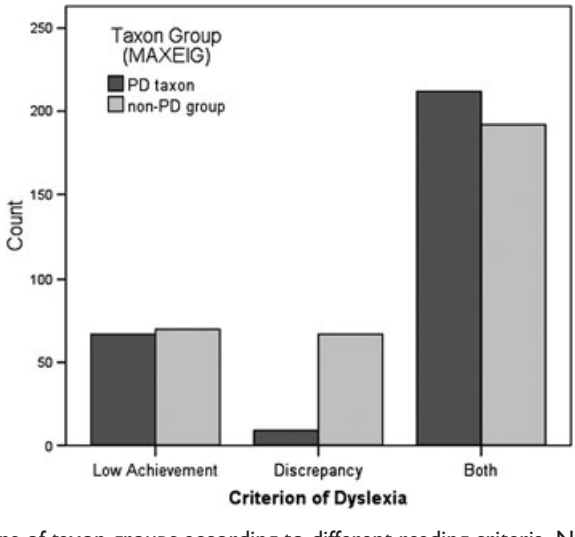

Figure 5. Proportions of taxon groups according to different reading criteria. Number of individuals categorized within each of the taxon groups (phonological deficit (PD), non-PD) as determined with the MAXEIG Hitmax procedure, shown within groups meeting different criteria for dyslexia (low achievement vs discrepancy criteria).

Discrepancy Criterion Subsample

Five-hundred and twenty children met this criterion, with 488 having complete data for the Hypothesis 1 indicators, and 520 having complete data for Hypothesis 2.

Hypothesis 1: PD Taxon

For these analyses, both the MAXEIG and MAMBAC procedures yielded fits to the empirically derived curves that indicated a taxonic structure to the data (CCFI's = 0.73 and 0.61, respectively), whereas the L-Mode curve fit index was not conclusive (CCFI = 0.57). Base rates ranged from 0.49 to 0.60 and were similar to the rates found with the whole sample.

Hypothesis 2: NSD Taxon

The MAXEIG and L-Mode procedures showed closer alignment of the data to dimensional structure (CCFI's = 0.28 and 0.42, respectively), whereas the MAMBAC fit to the empirically derived curves did not support dimensional structure (CCFI = 0.60). Base rate estimates ranged from 0.25 to 0.36, which are similar to those found for the whole sample.

In sum, the results for the discrepancy criterion subsample support the Hypothesis 1 finding of a PD taxon using the whole sample. Consistent results were found here with the subsample for MAXEIG and MAMBAC procedures, and the mean CCFI across the three procedures was 0.64. For Hypothesis 2, this subsample analysis showed results more closely aligned to dimensional latent structure for NSDs than the whole sample analysis, and the mean CCFI across the three procedures was 0.43 (Table 1). Thus, for the subsample meeting a discrepancy definition of dyslexia, there appears to be a continuum of rapid naming deficits (*Hypothesis 2*) but separate taxa that differ in kind with regard to the presence or absence of PDs (*Hypothesis 1*).

Low-Achievement Criterion Subsample

Five-hundred and ninety-one children met this criterion, with 517 having complete data for the Hypothesis 1 indicators and 591 having complete data for Hypothesis 2.

Hypothesis 1: PD Taxon

With this subsample, the MAMBAC, MAXEIG and L-Mode procedures supported a taxonic structure to data (CCFI = 0.67, 0.85 and 0.60, respectively). Base rate estimates ranged between 0.43 and 0.75, values that exceeded the whole sample estimates but that approximated earlier subtyping proportions (e.g. Lovett, 1995; Katzir *et al.*, 2008).

Hypothesis 2: NSD Taxon

Each of the three procedures, MAMBAC, MAXEIG and L-Mode, supported taxonic structure to the data (CCFI = 0.60, 0.63 and 0.59, respectively). Base rate estimates ranged from 0.21 to 0.43, similar to those found for the whole sample.

In sum, the results for the low-achievement-criterion subsample support the Hypothesis 1 finding of a PD taxon using the whole sample, with consistent results and a mean CCFI across the three procedures of 0.71. For Hypothesis 2, this subsample analysis shows more consistent results of a taxonic latent structure for NSDs than the whole sample analysis, and the mean CCFI across the three procedures was 0.61. Thus, for the subsample meeting a low-achievement-definition of dyslexia, there is evidence of taxa based on the presence versus absence of both rapid naming deficits (*Hypothesis 2*), and PDs (*Hypothesis 1*) (Table 1).

Comparison of Taxa Classified with MAXEIG Hitmax Procedure

Both the whole sample and subsample analyses supported taxonic structure of the data according to Hypothesis 1: testing for a PD taxon. Of particular interest is what might characterize the individuals with dyslexia who were classified into the complement group; that is, those without the putative PDs. As Schatschneider *et al.* (2002) acknowledge, 'additional scrutiny of this subtype may be particularly revealing in addressing the question of whether naming speed deficits exist independent of phonological processing' (p. 255). According to the DDH, most (but not all) dyslexic individuals without PDs would be expected to have issues with rapid naming, automatic word recognition and reading fluency. We therefore examined performance on measures of these skills for the non-PD complement group (identified with the whole sample—Hypothesis 1 MAXEIG Hitmax classification procedure above), in addition to variables that may contribute to reading impairments without necessarily being directly related to phonological processing. These included comprehension, spelling and vocabulary skills.

For each of the variables, portions of individuals scoring above and below cutoff scores (one standard deviation below the mean) are reported in Table 2, along with chi square statistics testing for a significant difference in proportions. As seen in the table, there were greater proportions of individuals with below average performance on rapid naming (RAN) and text fluency (GORT). For both oral and silent reading comprehension (GORT, WRMT-R), there were significantly more cases scoring in the below average range, although oral reading showed a bigger effect. However, there were equal numbers of below and average performers on measures of word reading efficiency (TOWRE), so this skill did not characterize the group one way or the other. In contrast, there were greater proportions of average performers on listening comprehension, spelling and vocabulary measures.

DISCUSSION

We tested two questions related to the DDH subtype model using taxometric methods as a novel approach to address inconsistency in the literature on the independence of phonological and NSDs in dyslexia. This approach differs from previous investigations of DDH subtypes, such as hierarchical regression techniques, because it does not attempt to tease apart PDs and NSDs within the same individual—rather, it attempts to classify

Table 2. Portions of individuals from the non-phonological deficit complement group (whole sample—Hypothesis 1) performing in the below average and average range on reading-related measures

Measure	Below average (*n*)	Average range (*n*)	χ^2
RAN letters	210	119	25.2**
TOWRE sight word efficiency	152	177	1.9
GORT oral reading fluency	261	65	117.8**
GORT oral reading quotient	254	75	326.7**
WRMT-R silent reading passage comprehension	179	133	6.8**
WIAT-II listening comprehension	53	276	151.2**
PIAT spelling	75	254	97.4**
PPVT-III vocabulary	75	254	78.8**

RAN, Rapid Automatized Naming; TOWRE, Test of Word Reading Efficiency; GORT, Gray Oral Reading Test; WRMT-R, Woodcock Reading Mastery; WIAT-II, Wechsler Individual Achievement Test Second Edition; PIAT, Peabody Individual Achievement Test; PPVT-III, Peabody Picture Vocabulary Test-III.
**indicates $p < .01$.

readers according to the presence or absence of these deficits in separate analyses. The present study does not address the issue of whether those with a DD are more severe cases of dyslexia, and relatedly whether their PDs and NSDs are additive (e.g. Schatschneider *et al.*, 2002; Compton *et al.*, 2001). Indeed, evidence for taxonic structure does not imply a lack of dimensional variation within latent taxa, given that 'both meaningful and non-meaningful variation is possible within latent classes' (Ruscio *et al.*, 2006, p. 11).

Addressing Hypothesis 1, we found support for the existence of latent classes of PD and non-phonological forms of developmental dyslexia. The three taxometric procedures, MAMBAC, MAXEIG and L-Mode, consistently indicated taxonic shape of the data curves as indexed by the curve fits' CCFI (Ruscio *et al.*, 2006). Examination of the non-phonological complement group revealed that two of the three predictions from the DDH held: more cases scored below average on rapid naming and reading fluency but not on automatic word recognition measures. In contrast, compared with the complement group, the PD taxon had higher proportions with below average spelling and vocabulary scores, indicating that this group had more pervasive problems. On the other hand, the non-phonological complement group had the same proportion with below average reading fluency scores as the taxon group, indicating this was a problematic area despite the lack of PDs. Individuals with dyslexia often have average or above listening comprehension, but their fluency problems prohibit them from using this underlying strength. This pattern of results indicates that global language skills are not an issue for these dyslexic readers, but instead rate of serial naming and reading text is problematic for many of them. These findings confirm areas of strength and weakness in different forms of dyslexia, which are important to our understanding and approach to remediation.

Addressing Hypothesis 2, we found mixed support for the latent structure of forms of developmental dyslexia with and without NSDs. Results from the three taxometric procedures were not as consistent according to the curve fits, with only one procedure supporting taxonic structure. Thus, a conclusion cannot be drawn from the present results with the set of NSD indicators used here.

Phonological and Non-Phonological Taxa

The finding of separate taxa for Hypothesis 1 implies that not all children in this dyslexic sample are alike with regard to language processing. The existence of latent taxa within a population is inferred to indicate differences in kind between the groups at some foundational level (Meehl, 1995). A body of evidence supports genetic contribution to developmental dyslexia in general and to specific subtypes in particular. Heritability studies of adoptive twins show different patterns of gene-environment contributions to individuals classified into different dyslexia subtypes. For instance, Castles, Datta, Gayan, & Olson (1999) showed a higher magnitude of genetic versus environmental influences in individuals classified with 'phonological dyslexia', in contrast to those classified with 'surface dyslexia'. Grigorenko *et al.* (1997, 2001) further showed that different phenotypes in dyslexia were related to different behavioural measures of cognitive skills. Their groups included a phonological phenotype and a word identification phenotype with slow colour and object naming. Different patterns of genetic contribution also have been demonstrated across various cognitive skills, including phonological versus rapid naming skills. Petrill, Deater-Deckard, Thompson *et al.* (2006), for example, found that among kindergarten to first-grade children, genetic variance contributed mostly to rapid naming, whereas environmental influences contributed significantly to phonological awareness and decoding. Thus, the different paths to reading disability (Katzir *et al.*, 2008) likely involve different

contributions from genetic predispositions and environmental factors and their interactions. These findings also indicate that the latent classes of dyslexia reported here may differ in constitutional origin at a genetic level.

The present set of results converges with others using various methodologies, which suggest that 'although phoneme awareness and RAN may have some general cognitive factors in common, they do not seem to share an underlying phonological deficit' (Boada & Pennington, 2006). For instance, Powell, Stainthorp, Stuart *et al.* (2007) found support for separate latent variables of rapid naming and phonological processing with structural equation models fit to the data of typically developing readers. The present findings extend this support of separate latent factors in development dyslexia.

Classification studies and prospective studies of children at familial risk for dyslexia also indicate that there is not a direct 1 : 1 correspondence between phonological and reading deficits (Morris *et al.*, 1998; Wolf & Bowers, 1999; Badian, 1997; Manis, Doi, & Badha, 2000; Lovett, Steinbach, & Frijters, 2000; Wimmer & Mayringer, 2002; Snowling, Gallagher, & Frith, 2003; Snowling, 2008). In addition, more recent subtyping studies confirm that non-PDs occur both with and without PDs in dyslexic samples. For instance, deviance analyses reveal varying profiles of dyslexia, including deficits in attention, visual and auditory sensory processing and executive function (Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007; Ramus, Rosen, Dakin *et al.*, 2003; Menghini, Finzi, Benassi *et al.*, 2010; Menghini *et al.*, 2010). Using cluster analysis, Heim, Tschierse, Amunts *et al.* (2008) differentiated an attention-based cluster from clusters with phoneme awareness alone and phoneme awareness plus sensory processing deficits in children with dyslexia.

In the present study, the selection of taxon indicators was guided by the DD model of dyslexia, and most of the indicators showed good discriminant validity (with the exception of Nonword Repetition; Table 3). Selection of NSD indicators was admittedly limited—rapid letter naming shows a unique contribution to reading performance, but criterion related measures are not currently known. As indicators of the taxon, we included RAN object naming because it shows early predictive value to reading, and the WISC-3 Coding subtest because it was a component of the discriminant function that best distinguished PD and NSD children (O'Rourke, 2002). However, other non-phonological factors are posited by dyslexia theories such as the magnocellular theory (Stein, 2001), the anchoring hypothesis (Banai & Ahissar, 2010), or the attentional shifting theory (Hari & Renvall, 2001). According to these models, alternative taxon indicators may include measures of sensory processing, executive function, and/or

Table 3. Discriminant validity for each indicator

Indicator	*d*
Hypothesis 1	
CTOPP elision	1.26
Sound Symbol Correspondence	1.67
CTOPP Nonword Repetition	0.82
TOWRE decoding efficiency	1.61
Hypothesis 2	
RAN letters	2.17
RAN objects	2.37
WISC III Coding	1.29

CTOPP, Comprehensive Test of Phonological Processing; TOWRE, Test of Word Reading Efficiency; RAN, Rapid Automatized Naming; WISC III, Wechsler Intelligence Scales for Children III.

attention. Thus, a naming speed/fluency deficit may be related to these processes as well, and in combination may better delineate a non-phonological taxon. Further work in this area is needed.

Definitional Criteria

We additionally addressed the issue of whether subtypes based on the DDH model would differ depending on how dyslexia was identified, either with traditional discrepancy criteria or broader low-achievement criteria. Would we find evidence of different subtypes within subsamples who met either definition? Word identification is found to correlate with phoneme awareness across a range of reading ability levels, whereas its association with naming speed appears to be more specific to dyslexic readers with IQ-achievement discrepancies (Wolf & Obregon, 1992; Ackerman & Dykman, 1993; Badian, 1994, 1996; Biddle, 1996). Across the three samples (whole, discrepant and low achievement), Hypothesis 1 testing for a PD taxon was supported. Hypothesis 2 testing for an NSD taxon was supported only for the subsample identified with low achievement, indicating a difference in kind with some low achievers having NSDs and others not involving this type of deficit. The discrepancy criterion sample supported a dimensional fit to the data, where NSDs appear to vary along a continuum. Further, for individuals with a discrepancy only, and average achievement, there was a greater proportion of non-phonological taxon members. These results indicate a divergent latent structure for subsamples diagnosed using different criteria (Table 1).

Depending on the dyslexia criterion used, samples may vary in composition with regard to their subtypes as well as their genetic basis. Genetic contribution to reading disorders interacts with IQ: there is greater genetic contribution within a high IQ range and more environmental contribution within a lower IQ range (Wadsworth, Olson, Pennington, & DeFries, 2000; Knopik *et al.*, 2002). As noted previously, contributions may vary between subtypes, following evidence of greater genetic and greater environmental influence on rapid naming and phonological processing, respectively. Within a discrepancy-identified sample, there will be a higher IQ range and presumably more genetically based cases of dyslexia. We surmise that such samples could consist of more genetically based NSD cases. The discrepancy subsample results reported here may thus reflect a greater proportion of a genetically based subtype indicated by a separate 'non-phonological' taxon and as supported by the dimensional structure for NSDs. These results have important implications for the types of individuals identified with reading disorders, and those not identified, when using different criteria. As Reynolds and Shaywitz (2009) point out, the response-to-intervention approach 'fails to consider bright students who struggle to read . . .. and who may nevertheless not be achieving up to their potential' (p. 46).

Although the present findings have important implications for the diagnosis, aetiology and treatment of dyslexia, several limitations should be noted and addressed in future research. The latent structure of deficits in cases of dyslexia may vary with time, as longitudinal research shows that rapid naming becomes a stronger predictor over time (Papadopoulos, Georgiou, & Kendeou, 2009). Examining only the second and third graders in the present sample supported taxonic structure for both PDs (mean CCFI = 0.55) and for NSDs (mean CCFI = 0.53). This is an important factor to consider longitudinally. Finally, non-phonological indicators require further investigation, as the current results support the multifactorial nature of deficits related to developmental dyslexia.

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NOTES

1. Comparison data were simulated using an iterative technique, which reproduced the distributional and correlational properties of the research data but simulated either dimensional or taxonic structure (Ruscio & Ruscio, 2004).
2. The traditional classification procedure for the double deficit hypothesis uses cutoff criteria of one standard deviation below the mean on Comprehensive Test of Phonological Processing Elision or Blending and Rapid Automatized Naming letter latency measures.
3. Here, the phonological deficit subtypes include the phonological deficit and double deficit types, which were determined with cutoff scores of one standard deviation below the mean on Comprehensive Test of Phonological Processing Elision or Blending tests.
4. For example, 'Matthew effects' (Stanovich, 1986) refer to increased reading experience contributing to higher verbal components of intelligence tests; thus, the 'rich' who tend to read more get 'richer' in their IQ scores.

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