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Mixture growth models of RAN and RAS row by row: insight into the reading system at work over time

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Abstract Children ($n = 122$) and adults ($n = 200$) with dyslexia completed rapid automatic naming (RAN) letters, rapid automatic switching (RAS) letters and numbers, executive function (inhibition, verbal fluency), and phonological working memory tasks. Typically developing 3rd ($n = 117$) and 5th ($n = 103$) graders completed the RAS task. Instead of analyzing RAN/RAS results the usual way (total time), growth mixture modeling assessed trajectories of successive times for naming 10 symbols in each of five rows. For all three samples and both RAN and RAS, two latent classes were identified. The "faster" class performed slowly on the first row and increased time by *small increments* on subsequent rows. The "slower" latent class performed *more slowly* on the first row, and children, but not adults, increased time by *larger increments* on subsequent rows. For children, both the initial row (automaticity index) and slope (sustained controlled processing index) of the trajectory differentiated the classes. For adults, only the initial row separated the classes. The longest time was on row 3 for RAN and row 4 for RAS. For the typically developing 5th graders, close in age to the children with dyslexia, the trajectories were flatter than for children with dyslexia and only the slower class (4%) showed the peak

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on row 4. For children with dyslexia, inhibition predicted RAN slope within the slower latent class and phonological working memory predicted RAS slope for both latent classes. For adults with dyslexia, inhibition and phonological working memory differentiated both latent classes on RAN intercept and RAS slope. Taken together, RAN, which may assess the phonological loop of working memory, and RAS, which may assess the central executive in working memory, may explain the timing deficit in dyslexia in sustaining coordinated orthographic-phonological processing over time.

Keywords Rapid automatic naming (RAN) · Rapid automatic switching (RAS) · Dyslexia · Inhibition · Phonological working memory · Automaticity · Controlled processing

Introduction

Definition and working memory theoretical framework for dyslexia

The International Dyslexia Association currently defines dyslexia as unexpectedly low accuracy and/or rate of oral reading or spelling of neurobiological origin (Lyon, Shaywitz, & Shaywitz, 2003). Thus, dyslexia is a dysfunction in lexical or word processes—that is, word reading and spelling—but not in the verbal comprehension processes. Another specific reading disability does affect reading comprehension and may or may not include impaired word-level processes that characterize dyslexia. Procedures for operationalizing the IDA definition of dyslexia in a decade-long family genetics study are explained in the methods section.

Many theories of dyslexia have been proposed, each of which is likely to explain part of this complex developmental reading disorder. Research evidence for the phonological basis of this disorder is substantial (e.g., Morris et al., 1998). Likewise, the research evidence for rapid automatic naming (Denckla & Rudel, 1976; Wolf, Bally, & Morris, 1986) and rapid automatic switching deficits, which occur alone or in combination with phonological deficits, is compelling (Wolf & Bowers, 1999). Even in phonologically regular orthographies, children with dyslexia manifest rapid automatic naming deficits (e.g., Wimmer & Mayringer, 2001), suggesting that the vulnerability in dyslexia extends beyond phonological decoding alone. Dyslexics have also been shown to have deficits in orthographic coding (Berninger, Abbott, Thomson, & Raskind, 2001; Berninger et al., 2006a; Olson, Forsberg, & Wise, 1994), working memory (e.g., Swanson, 2000), executive functions (e.g., Swanson, 1993), and timing the coordination of mental processes (e.g., Bowers & Wolf, 1993; Breznitz, 2002; Waber, 2001; Wolf, 1999; Wolff, Cohen, & Drake, 1984). Others have attributed the problems in dyslexia to lack of automaticity (Nicolson, & Fawcett, 1990).

Berninger et al. (2006b) turned to working memory for a construct that may integrate these various theoretical explanations for dyslexia. The concept of working memory has evolved since first proposed and studied by Baddeley and colleagues (e.g., Hitch & Baddeley, 1976). Originally working memory was thought to be a system with a phonological or visual-spatial storage unit, an articulatory loop for maintaining information in the temporary storage unit, and a central executive. Current models (see Baddeley, 2002) allow for other kinds of storage, including an episodic buffer for storing novel stimuli, a *phonological (not articulatory) loop* that coordinates the integration of different codes in the episodic buffer and guides the learning of new words through overt naming, and the central executive's functions have expanded beyond supervisory attention alone. Moreover, brain imaging research has shown that not only phonological word forms (Aylward et al., 2003; Booth et al., 2001; McCrory, Frith, Brunswick, & Price, 2000) but also orthographic (e.g., Booth et al., 2001; Cohen et al., 2002; Crosson et al., 1999; Richards et al., 2005, 2006a) and morphological (e.g., Aylward et al., 2003; Richards et al., 2005, 2006, 2006a, 2006b) word forms are stored in working memory. The time-limited phonological loop (Kail, 1984) represents the sound patterns of familiar words and works closely with the episodic buffer (a multimodal coding system that integrates different kinds of codes) and the central executive to coordinate these codes in time (Baddeley, Gathercole, & Papagno, 1998). Miyake et al. (2000) identified three separable executive functions in verbal working memory: mental set shifting, inhibition, and monitoring and updating.

On the basis of this evolved model of working memory, a structural model of verbal working memory that included storage (phonological, orthographic, and morphological word forms), a time-sensitive phonological loop, and executive functions (for inhibition and switching mental set) explained the variance in a variety of reading and writing skills in children and adults with dyslexia (Berninger et al., 2006b). Each of the components of working memory had a phonological core deficit, consistent with the theories relating dyslexia to both phonological and working memory deficits. Cross-cultural twin studies also report phonological and verbal working memory deficits in the preschoolers that predict future dyslexia during the school years (e.g., Byrne et al., 2002).

Focus: what RAN and RAS measure and their significance for dyslexia

The focus of this study was, therefore, on how the rapid automatic naming (RAN) and rapid automatic switching (RAS) deficits that characterize developmental dyslexia may shed light on the working memory deficits that also characterize developmental dyslexia. Although Wolf and Bowers (1999) detailed a theoretical account of the complexity of RAN that allows for all the components of working memory (supervisory attention, orthographic and phonological codes, executive coordination of codes in time), many other investiatgors have tried to explain RAN only on the basis of merely speeded phonological retrieval processes. However, given the model of a working memory system just described, RAN for letters (Denckla & Rudel, 1976; Wolf & Denckla, 2004; Wolf et al., 1986) may be a measure of the time-sensitive phonological loop because it involves time sensitive cross-code integration (orthographic sublexical letter representations and phonological lexical representations of names) and overt articulation of familiar phonological word forms for strings of unrelated letters (stored in an episodic buffer). For RAN letters, the category of the visual stimulus to be named is kept constant. Repeated, speeded naming of letters over the time course of many trials is required—that is, sustained involvement of the naming of letters in a working memory system, which like the reading system requires the coordination of orthographic and phonological processes over time.

Rapid automatic switching (Wolf, 1986), on the other hand, may assess part of the supervisory attention system that regulates constantly switching among mental sets for stimuli from alternating categories—letters and numerals. Inhibition, which is the ability to suppress irrelevant information and focus on relevant information, may underlie ability to constantly switch mental set (see Miyake et al., 2000). Both inhibition and set switching may contribute to the temporal coordination and overall efficiency of verbal working memory (Gunter, Wagner, & Friederici, 2003). Thus, RAN and RAS are probably robust predictors of timed reading and writing skills (e.g., Berninger et al., 2001) because they model the phonological loop and central executive of verbal working memory, respectively, which jointly contribute to the timing and efficiency of verbal working memory.

RAN and RAS have been assessed in varied ways in different research studies. In the current study RAN for letters and RAS for letters and numerals were given individually to all participants who were shown laminated cards, each of which had five rows of either 10 letters each or 5 letters and 5 digits. These were the pre-publication stimulus materials (Wolf & Biddle, 1994, Unpublished norms for RAN and RAS tasks) of the recently published RAN/RAS (Wolf & Denckla, 2004). These measures had been used in many of the longitudinal and other studies by Wolf and colleagues and other research groups. The same letters or set of letters and digits was used in each row but in different orders. As a child completed each row, the tester recorded the current time on a hand held running stopwatch. At the end of the test session, the running times for adjacent rows were subtracted to determine the number of seconds required to name all 10 written symbols in each of the 5 rows.

Neither RAN nor RAS are direct measures of literacy and one would not recommend teaching this task to improve literacy skills. Thus, it is difficult for some educators and researchers to understand *why these measures are important* in assessing and investigating either normal or disabled reading and writing. For one thing, many fields of basic science have advanced by studying markers of a disorder or construct that are not synonymous with the construct itself. As already explained our working hypothesis was that RAN is a marker for the efficiency of the phonological loop and RAS is a marker for the efficiency of the central executive of the verbal working memory system that supports the reading system at work. Research to date has validated that RAN and/or RAS predict reading and writing skills of typically developing children, at-risk readers, and dyslexics. (See Wolf, Bowers, & Biddle, 2000; Wolf, 2001) for additional reviews of this research literature.

Typical beginning readers

Two robust predictors of beginning reading achievement are RAN and phonological awareness (Manis, Seidenberg, & Doi, 1999). RAN, which assesses ability to form automatic associations between stimuli that have arbitrary relationships, like orthographic symbols and their spoken names, is a stronger predictor of orthographic representations of written words than phonological awareness. Ability to analyze component sounds in spoken words, that is, phonological awareness, is a stronger predictor of phonological decoding (translating written words into spoken words) (Manis et al., 1999).

At-risk readers

In a study of first graders (Compton, 2000a), the ability to pronounce real words and pseudowords (an index of phonological decoding) was assessed repeatedly across the school year. A set of reading-related measures (letter names and sounds, phoneme and orthographic awareness, phoneme–grapheme correspondences, and RAN total time) was evaluated for the unique contribution of each measure to predicting the intercept and the slope of growth curves for real word and pseudoword reading. RAN based on total time uniquely predicted the intercept but not the slope across repeated assessments of both real word and pseudoword reading. In another study (Compton, 2000b), first graders were measured at the middle of the school year. Their growth in real word and pseudoword reading was best predicted by phoneme awareness, phoneme–grapheme knowledge, and initial real word/pseudoword reading in the control group of able readers and by RAN total time, phoneme–grapheme knowledge, and phoneme awareness in the at-risk readers group. RAN total time also predicted response to intervention in the at-risk readers who were subsequently given supplementary reading instruction. In yet another study of first graders (Compton, 2000c), the relationship between RAN and phonological decoding was shown to be reciprocal. RAN total time prior to learning to decode was related to level of subsequent decoding skill, but improvement in decoding was related to improvement in RAN (decrease in total time). In a subsequent study of first graders (Compton, 2003), the relationship between RAN total time (not accuracy) at the beginning of first grade contributed uniquely to reading achievement (identifying real words).

Dyslexics

Denckla and Rudel (1976) showed that RAN total time is associated with dyslexia, a specific reading disability not related to impaired cognition, and dyslexics have slower naming times than good readers on this measure that is related to reading but does not require reading. Wolf and Bowers (1999) showed that dyslexics who have a double deficit in both phonological awareness and RAN time have the most severe forms of dyslexia. In cross-language studies, dyslexics who speak languages that have a transparent orthography (one-to-one relationship between letters and phonemes) tend to show a RAN time deficit rather than phonological awareness deficit (e.g., Wimmer & Mayringer, 2001).

At-risk spellers

For at-risk second grade spellers, latent variable mixture growth modeling based on number of correctly spelled words during independent composing (following explicit instruction in alphabetic principle and connections between units of written words and units of spoken words) identified three classes of responders on the basis of initial score (intercept) and rate of change (slope): low initial and slow growth; high initial and fast growth; and highest initial but slow growth (Amtmann, Abbott, & Berninger, in press). All children increased the number of correctly spelled words in their compositions over 24 weeks but at different rates of change, which were not predicted solely from initial performance. RAN letters differentiated the three latent classes of response to instruction.

Significance of the current research approach and hypotheses

Novel approach to RAN and RAS times

The research findings just reviewed are based on the total time score for RAN or RAS. In this study, RAN and RAS performance was analyzed in a novel way—row by row— and growth mixture modeling was used to identify classes of response sustained over time based on the row-by-row times on RAN or RAS. We predicted that individuals with dyslexia would take longer to read the first row, that is, would have higher intercepts than normal readers. However, the intercept was thought to reflect only the initial automatic retrieval of names for orthographic symbols, that is, phonological loop function.

Time to complete the later parts of the task is more likely to reflect the ability to sustain in working memory the rapid retrieval of names from long-term memory. Change in time from row to row is more likely to reflect executive functions of working memory that sustain controlled search through long-term memory for the name associated with an orthographic symbol. While repeated practice may improve time (decrease it) for some skills, processing deficits in dyslexia (e.g., habituation from performing a repeated, effortful controlled search task in working memory) may lead to increased times for each subsequent row.

Finally, we wondered whether differences between children and adults with dyslexia and between children with dyslexia and typically developing children in latent classes were related to executive functions (e.g., inhibition) or working memory. In particular, differing relationships between the working memory measures and the latent class trajectories might illuminate our understanding of how automatic versus controlled, effortful processing (Schneider & Shiffrin, 1977) contributes to dyslexia or typical reading and writing development.

Growth mixture modeling

Many applications of growth curve modeling (such as conventional growth curve models) allow for across-individual heterogeneity, but all individuals are assumed to come from the same population. Numerous research questions, however, involve grouping individuals based on their developmental trajectories into categories that contain individuals with distinctive pattern of development. For instance, researchers and clinicians may be interested in finding subgroups of individuals who may benefit from the same type of intervention or subgroups that are at a greater risk of, for instance, reading failure than others. On many occasions, researchers are interested in identifying and studying subgroups or subpopulations because the ability to predict membership in these classes or subgroups might provide opportunities for appropriate treatment.

Growth mixture modeling (GMM) is a method specifically developed to identify statistically homogeneous groups that share a similar latent trajectory of growth. A relatively new, empirically based approach, GMM allows researchers to examine potential unobservable heterogeneity in a sample, that is, to investigate whether reliable, qualitatively different subgroups of individuals with similar growth trajectories could be modeled (Abbott, Amtmann, & Munson, 2003).

In GMM, individuals are allowed to vary around the latent class mean growth curves (Lubke & Muthern, 2005; Muthen, 2004) and individual variation continues to be accommodated. GMM is an extension of the conventional random effect growth modeling that combines latent growth curve (Muthen & Shedden, 1999) modeling and cluster analysis (finite mixture analysis). GMM is a method for analyzing repeated measures that does not assume that all individuals in the sample come from the same population. GMM involves modeling change over time and examining whether there are differences in patterns of change. GMM goes beyond conventional growth curve modeling when the developmental trajectories can be grouped into distinguishable classes and baseline covariates are effective in predicting class membership. For examples of this methodology, see Muthen, Khoo, Francis, and Boscardin (2000), Oxford et al. (2003), Shaeffer, Petras, Ialonga, Poduska, and Kellam (2003), Parrila, Aunola, Leskinen, Nurmi, and Kirby (2005), and Muthén et al. (2002).

Research hypotheses

We tested three hypotheses. The first was that when RAN and RAS are analyzed row by row, individual differences in the trajectories, defined by intercept and slope, of naming times across rows will be observed in children and adults with dyslexia. The second was that when RAS is analyzed row by row, individual differences in the same trajectories of naming times across rows will also be observed in typically developing children of comparable age. This hypothesis could not be tested for RAN because only the RAS used in the family genetics study was available for the typically developing sample. The third hypothesis was that individual differences in executive function (e.g., inhibition) and in phonological working memory will be related to the individual differences in the RAN and RAS trajectories in children and adults with dyslexia. This hypothesis could not be tested in the typically developing children because the same predictor measures of executive function and phonological working memory were not available for this group.

Method

Participants

Research inclusion criteria for dyslexia

For a decade, a family genetics study of dyslexia has administered a test battery of oral reading (accuracy and rate of single real words, pseudowords, or passages) and spelling, verbal intelligence, and processes related to reading and writing to identify children and adults who meet criteria for dyslexia. To operationally define unexpectedly low reading and spelling, WISC 3 (Wechsler, 1991) or WAIS-R (Wechsler, 1981) Verbal IQ was used instead of Full Scale IQ because research studies have shown Verbal IQ is a better predictor of reading achievement than Nonverbal IQ in referred and unreferred samples (Greenblatt, Mattis, & Trad, 1990; Swanson, Carson, & Sasche-Lee, 1996; Vellutino, Scanlon, & Tanzman, 1991), and thus could be an indicator of what expected reading achievement might be. For children, Verbal IQ was based on subtests that load on the Verbal Comprehension factor and not those that load on a working memory or freedom from distractibility factor (e.g., arithmetic or digit span) that is known to be lower in children with reading disabilities.

Only children with Verbal IQs at or above a standard score of 90 (25th %tile) were included in the study. We studied dyslexia in the top 75% of the population along the verbal intelligence continuum because comorbid neurodevelopmental and neurogenetic disorders are more prevalent in the population falling in the bottom quartile on intelligence tests (e.g., Liederman, Kantrowitz, & Flannery, 2005); such disorders might explain other kinds of reading disabilities, which are not unexpected based on the developmental profiles of cognitive, memory, language, motor, and/or attention/executive functions associated with the disorders. Also, specific reading disability (no other developmental disorders) is more likely to have a genetic basis in individuals with higher IQs (Wadsworth, Olson, Pennington, & De Fries, 2000).

Children met definitional criteria for dyslexia and qualified their families for participation in the study if (a) reading and/or spelling achievement was at least one standard score below the Verbal IQ on any of the measures of accuracy and rate of reading or accuracy of spelling in the test battery; and (b) the reading and spelling achievement fell below the population mean (50%tile). Children identified using this operational definition were impaired on multiple measures of reading and spelling, their Verbal IQ fell, on average, at the upper end of the average range, and they were, on average, reading and spelling words at about one standard deviation below the mean and about one and two-thirds standard deviation below their Verbal IQs. In addition, they had associated processing deficits in phonological, orthographic, and/or rapid automatic naming skills (Berninger, Abbott, Thomson, & Raskind, 2001) and in components of working memory (word form storage), time-sensitive phonological loop, and executive functions, each of which has a phonological core (Berninger et al., 2006b). Except for phonological processing problems, these children did not, on average, have severe oral language problems (e.g., in morphological or syntactic awareness). However, both the children (RAN mean z-score –1.21; RAS mean z-score –.75) and adults (RAN mean z-score –1.43; RAS mean z-score –1.66) with dyslexia were significantly impaired in RAN letters and RAS letters and numbers based on total time.

We also note that in a study of the children who did not meet these inclusion criteria, but who obviously had severe reading disability, we documented that those who did not show IQ-achievement discrepancy had significant oral language problems, especially in morphological and syntactic awareness, and were more likely to have had histories of difficulty in learning oral language during the preschool years (Berninger & O'Donnell, 2004). That is, they fit the profile of language learning disability (Butler & Silliman, 2002; Wallach & Butler, 1994) rather than of dyslexia. Children with language learning disability first have difficulty learning oral language and then have difficulty learning to use oral language to learn—both learning written language and learning in general in verbally oriented school settings (Berninger, 2006, in press; Berninger, Nagy, Richards, & Raskind, in press). Because we recognize that dyslexics (spared comprehension) and language learning disabled (impaired comprehension) may be confounded in much of the research literature on reading disability, we recognize that the results reported here may be generalized only to those who have a specific word decoding, word reading, and/or spelling disability without concurrent significant oral language or verbal comprehension problems. Although we do not believe that IQ-achievement discrepancy defines all reading disabilities or should be the only way to qualify students for special services at schools, our research evidence shows that (a) untreated dyslexia is characterized by discrepancy between Verbal IQ and oral reading (accuracy or rate of single real or pseudowords or passages) or spelling *plus* research-supported processing deficits, and (b) untreated language learning disability is characterized by severe impairment in reading comprehension and word reading (and decoding and spelling) and related processing deficits that include those for dyslexia plus additional oral language deficits (Berninger, 2006, in press; Berninger et al., in press). This article focuses only on dyslexia.

Samples in current study

Three samples participated in this new study: (1) children (probands) who met inclusion criteria for dyslexia and qualified their families for a genetics study (see Berninger et al., 2006b, for description of child sample), (2) parents of the probands who also met the research criteria for dyslexia (see Berninger et al., 2006b, for description of adult sample), and (3) a sample of typically developing children participating in a longitudinal study of the development of reading and writing skills (see Berninger et al., 2006a, for description of sample—cohorts 1 and 2 in year 3). All participants were native speakers of English.

Sample 1: probands

Children were included in the family genetics study if (a) their Verbal IQ (based on information, similarities, vocabulary, and comprehension for the Verbal Comprehension Factor) was at least 90 (lower limit of average range); and (b) their accuracy or rate of single word reading or spelling or oral text reading was below the population mean and at least a standard deviation below their Verbal IQ. All children had had special education, supplementary instruction in the general education, and/or private tutoring and continued to struggle with reading and writing. More information on ascertainment for purposes of a family genetics study is included in Berninger et al. (2006b). Of the 122 children, 80 were male and 42 were female. On average, the children were impaired on multiple measures of oral reading and spelling (Berninger et al., 2006b). They were on average 138.3 months (SD = 20.6 months) (11 years 6 months) old. Although the majority were European-American (88.5%). About 5.7% were from ethnic minority backgrounds (3.3% Asian-American; 1.6% African-American; 0.8% Native American; and 3.3% other; ethnicity was not reported for 2.5%). Parental level of education (mother's level reported first and then father's) ranged from high school (5.7%; 13.3%) to community college/vocational training (22.1%; 24%) to college (52.1%; 36.7%) to graduate degree (19.8%; 25.8%); this information was missing for .8%.

Sample 2: adults with dyslexia

Of the biological parents of the probands in Sample 1, 115 fathers and 85 mothers were affected (met the same inclusion criteria as their children). These affected adults were also impaired on average in reading and writing but were not as impaired as their children (Berninger et al., 2006). Mean age of the affected adults was 543.2 months (SD = 55.6 months) (45 years 3 months). Their ethnic background differed slightly from the children some of whom were the offspring of multi-ethnic marriages. Most were European-American (93.5%) and 5.5% were minority (2.5% Asian-American; 1.5% African-American; .5% Hispanic; 1.0% Native American); and 1% were other. Parents' level of education ranged from less than high school (1%) to high school (7%), to community college/vocational training (22%), to college (43.5%) to graduate degree (23.5%); no information was available for 3%.

Sample 3: typically developing children

Sample 3 was recruited from a large metropolitan school district and other local schools. Letters announcing the opportunity to participate were sent by the large metropolitan school district to parents. If interested, parents contacted the research coordinator and received information about the nature of the study. If parents decided to participate, informed consent was obtained. There were 117 3rd graders and 103 5th graders. The average age of the 3rd graders was 104.24 months (8 years 8 months) (SD = 3.64 months) and of the 5th graders was 127.56 months (10 years 8 months) (SD = 3.75 months). Of the 220 participants, 103 were boys and 117 were girls. The 3rd graders included 25% students who were Asian American, 5% African American, 65% European American, .9% Hispanics, 2% Native American, and 3% "other." The 5th graders included 23% Asian American, 8% African American, 64% European American, .9% Hispanics, .9% Native American, and 3% "other." There was a range in levels of mothers' education. For the 3rd graders, 2% had less than a high school education, 13% had a high school education, 9.5% had community college or vocational education but less than a college degree, 38.5% had an undergraduate education, and 33% had graduate level degrees; information was missing for 3%. For the 5th graders, 1% had less than a high school education, 7% had a high school education, 13% had community college or vocational education but less than a college degree, 38% had an undergraduate education, and 34% had graduate level degrees; information was missing for 7%.

Data collection procedures

All participants were tested individually in private rooms by highly trained graduate research assistants working under supervision. To qualify for participation in the family genetics study, the following skills were assessed with measures in parentheses to evaluate whether children met the criteria for dyslexia and, if they did, their parents and family members were given the same measures: accuracy of real word reading (*Woodcock Reading Mastery Test-Revised*, WRMT-R Word Identification, Woodcock, 1987), accuracy of pseudoword reading (WRMT-R Word Attack), rate of real word reading (*Test of Word Reading Efficiency*, TOWRE, sight word efficiency, Torgesen, Wagner, & Rashotte, 1999), rate of pseudoword reading (TOWRE phonemic reading efficiency, TOWRE, 1999), accuracy and rate of oral reading of passages (*Gray Oral Reading Test, Third Edition*, GORT 3, Wiederholt

& Bryant, 1992), and spelling (*Wide Range Achievement Test*, Third Edition, Wilkinson, 1993; Wechlser Individual Achievement Test, Psychological Corporation, 2002), and prorated Verbal IQ (based on information, similarities, vocabulary, and comprehension on the Wechsler Intelligence Scale for Children, Third Edition, WISC 3, Wechsler, 1991). Adults were given the same reading and spelling measures but the Wechsler Adult Intelligence Scale, Revised (WAIS-R, Wechsler, 1981). The WAIS-R prorated Verbal IQ is based on the same four subtests as the WISC 3 plus digit span. In addition, each participant in Study 1 (children with dyslexia) and Study 2 (adults with dyslexia) was given the measures in the next section. The typically developing children were from a longitudinal study of writing and reading–writing connections (Berninger et al., 2006a) for whom the 1994 prepublication version of the Wolf and Denckla version of RAS was available only in year 3 when children were in grades 3 or 5, and the Wolf and Denckla version of the RAN for letters was never given.

Measures

Rapid automatic naming (RAN) (prepublication version, Wolf & Denckla, 2004)

RAN and RAS (Wolf & Biddle, 1994, Unpublished norms for RAN and RAS tasks) were administered. RAN letters, which required oral naming of 10 symbols of a constant category in each of five rows, assesses speeded integration of the orthographic and phonological codes. Test–retest reliability over 9-months was .65 for RAN (Berninger et al., 2006b). RAN Letters was only available for children and adults with dyslexia.

Rapid alternating switching (RAS) (prepublication version, Wolf & Denckla, 2004)

This test requires oral naming of switching categories (letters and numbers) displayed as 5 rows of 10 symbols each (5 letters and 5 alternating digits). It assesses ability to switch attention or mental set rapidly. Test–retest reliability over 9-months was .81 for RAS (Berninger et al., 2006b). RAS was available for both dyslexic groups and the typically developing children in grades 3 and 5.

RAN and RAS row by row measures

Hand-held stopwatches were used to record the time as each participant completed each row of the RAN Letters or RAS Letter/Numbers. Subsequently the tester subtracted the times between rows to determine the amount of time (in seconds) for reading each row. Only times in seconds (fractions of seconds were truncated to whole seconds) were used in the analyses. These row-by-row times are the repeated measures in the following growth mixture analyses. Errors rarely occurred and did not show sufficient individual differences to enter them into analyses. Names of alphabet letters (1–26) and numerals (0–9) are highly familiar and practiced in the ages studied.

Delis–Kaplan executive function system (D-KEFS; Delis, Kaplan, & Kramer, 2001)

Color Word-Form Inhibition and Verbal Fluency—Repetitions subtest scores were analyzed as predictors of classes of response in naming times for 5 sequential rows with 10 letters (or letters and digits) in each row. Test–retest reliability coefficients for the D-KEFS Color-Word Form subtests ranged from .62 to .76. The Inhibition subtest measures the time required to rapidly name the ink color of color words written in a different color of ink; this score reflects the ability to suppress irrelevant information (name of color word) and attend to relevant information (color of ink). Verbal Fluency Letters, which has test–retest reliability coefficients that range from .36 to .80, requires rapid generation, within a time limit, of spoken words that start with a particular letter. Repetitions during this task are interpreted as a failure to monitor and update working memory.

Phonological working memory

The Woodcock Johnson-Revised (WJ-R; Woodcock & Johnson, 1990) Numbers Reversed subtest requires storage of heard numerals and retrieval and production of their number names. Participants listen to a sequence of digits and are then asked to recall and name them in reverse order. Internal consistency reliabilities range from .77 (9 years) to .83 (13 year olds) (Woodcock & Johnson, 1990).

Procedures for statistical analyses

Latent growth mixture modeling (Muthen, 2003, 2004; Muthen & Muthen, 2000) was used to investigate whether latent classes of individuals that systematically differed in their initial level of performance and/or the shape of the trajectories could be statistically identified. This analysis modeled the number of seconds to read each row of the RAN and RAS tasks. The factor loadings for the intercept were set to 1 for each measurement point. To estimate the row by row times, the growth model with the factor loadings for the slope were set at 0, 1, and 2 for rows 1, 2, and 3 respectively. The factor loadings for rows 4 and 5 were freely estimated. By assigning 0 as the growth coefficient for the first row, the time for row 1 was designated as the intercept. Figure 1 shows the GMM model estimated. GMM estimates the mean growth trajectory for each identified class. Individual variation is captured around the growth curves by estimating the variance of each growth factor within each class (Muthen & Muthen, 2000). In summary, the intercept growth factor

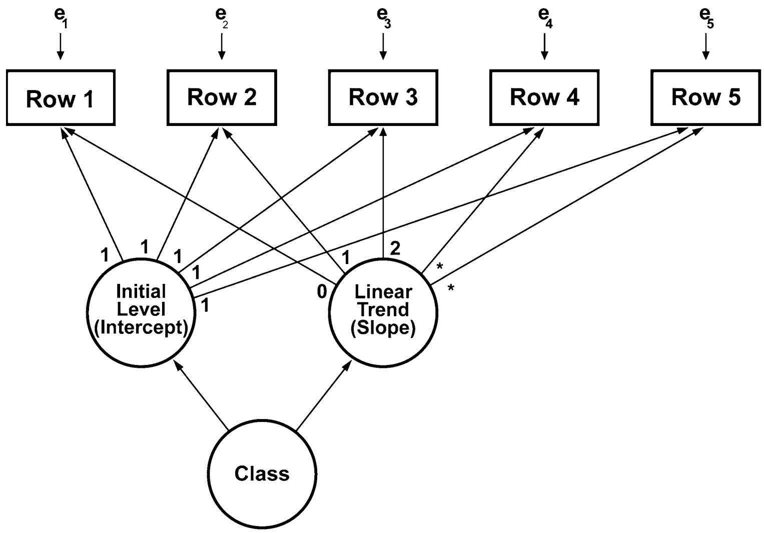

Fig. 1 Growth mixture model for abstracting classes of latent factors (e.g., one in this figure) based on common indicators (intercept and slope) for multiple data sets (each of five rows in a rapid naming task)

(initial level) represents the systematic part of the variation in RAN/RAS scores for row 1; that is, the intercept is the number of seconds that it takes to read the first row averaged over the members in a class. The slope growth factor models the systematic part of the increase in the number of seconds it takes to read each subsequent row; that is, it models the average growth for individuals in the class.

Steps in the analyses

The analyses were conducted in two main steps. In step one, analyses focused on the fit of linear (as specified above) models of growth, the number of latent trajectory classes, and the comparison of competing models. Descriptive statistics for the outcome variable (the number of seconds per row) are shown in Table 1. In stage two, predictors of latent growth mixtures were analyzed.

In Fig. 1, the mean and variance of the latent factors of intercept and slope represent group (means) and individual (variances) variations in intercept and slope. The oval labeled Class represents the categorical latent variable that represents the modeling of latent trajectory classes that differ in intercepts and slope. We followed the procedures described in Muthen and Muthen (2000) and Muthen (2001, 2003) to select the number of classes. More detailed information about the methods for fitting GMMs can be found in McLachlam and Peel (2000), Muthen and Shedden (1999), and Muthen and Muthen (1998–2006).

The final model was selected using both substantive (e.g., interpretability, clinical usefulness) as well as statistical considerations. To compare the fit of

Table 1 Descriptive statistics for children with dyslexia ($n = 122$ for RAN and 121 for RAS), affected parents ($n = 199$ for RAN and 200 for RAS), and typically developing 3rd graders ($n = 119$) and 5th graders ($n = 105$) for RAS and predictor executive functions and working memory measures

	Min	Max	Median	Mean	SD
RAN letters					
Children with dyslexia					
Row 1	2	13	5.00	5.17	1.957
Row 2	3	16	6.00	6.40	2.355
Row 3	4	20	6.00	6.89	2.735
Row 4	3	18	6.00	6.82	2.620
Row 5	3	28	6.00	6.54	2.805
Adults with dyslexia					
Row 1	1	12	3.00	3.50	1.385
Row 2	2	10	4.00	4.02	1.239
Row 3	2	11	4.00	4.33	1.307
Row 4	2	9	4.00	4.11	1.141
Row 5	2	9	4.00	4.09	1.133
RAS letters/numbers					
Children with dyslexia					
Row 1	2	13	5.00	5.80	2.240
Row 2	4	34	7.00	7.80	3.641
Row 3	4	23	7.00	8.13	3.433
Row 4	5	29	10.00	11.78	5.435
Row 5	4	22	8.00	8.61	3.197
Adults with dyslexia					
Row 1	2	9	3.00	3.51	1.176
Row 2	2	10	4.00	4.25	1.222
Row 3	2	13	4.00	4.44	1.320
Row 4	2	15	5.00	5.45	1.844
Row 5	2	10	4.00	4.58	1.264
Typically developing 3rd graders					
Row 1	3	16	5.00	5.97	2.170
Row 2	2	17	7.00	6.93	2.524
Row 3	3	18	7.00	7.64	2.922
Row 4	5	31	11.00	11.81	5.551
Row 5	3	24	9.00	9.29	3.606
Typically developing 5th graders					
Row 1	2	10	4.00	4.70	1.623
Row 2	3	17	5.00	5.58	1.994
Row 3	2	13	6.00	6.07	2.242
Row 4	4	24	8.00	7.99	3.647
Row 5	3	15	7.00	6.76	2.238
Predictor measures					
Children with dyslexia					
Delis–Kaplan color-word form inhibition ($n = 118$)	1	17	8.00	7.72	3.074
Delis–Kaplan verbal fluency repetitions ($n = 122$)	1	13	8.00	7.00	2.509
WJ-R digits backwards ($n = 122$)	47	152	92.00	93.94	15.699
Adults with dyslexia					
Delis–Kaplan color-word form inhibition ($n = 199$)	1	15	10.00	9.42	2.782
Delis–Kaplan verbal fluency repetitions ($n = 200$)	1	13	10.00	8.99	2.939
WJ-R digits backwards ($n = 200$)	62	180	109.00	110.11	22.049

models with the different number of classes we used the Bayesian information criterion (BIC, Schwartz, 1978) statistic. BIC is a goodness-of-fit statistic that takes into account and penalizes for the number of parameters estimated. Models with a lower BIC value are considered to have better fit. The BIC values were obtained for one-, two-, and three-class models. The second statistical criterion used was the classification quality. Entropy (Ramaswamy, DeSarbo, Reibstein, & Robinson, 1993) is a statistic that uses the estimated conditional class probabilities to summarize the classification quality of a model, that is, to measure the degree to which the different latent classes are clearly distinguishable in the data. Entropy values range from zero to one. The lower the entropy value, the lower the classification quality of a model. The last criterion was the usefulness of the latent classes in practice, that is, how many individuals were in each class and whether the different trajectories would represent meaningful differences in clinical practice.

The Mplus statistical package (Version 4.0; Muthen & Muthen, 1998–2006) was used to perform all statistical analyses. Measures of classification quality, such as posterior probabilities for each class, including entropy, are provided by Mplus. In addition, a number of different statistical indices are provided to be used to compare model fit between different models. The small amount of missing data (<1%) on measured variables was modeled using Mplus's missing at random. To minimize local optima solutions that are often encountered with mixture modeling, the use of several different sets of starting values is recommended and this procedure has been incorporated in Version 4.0 of Mplus.

Once the latent classes were modeled, we investigated whether the class members were statistically significantly different on working memory and executive functions that we hypothesized might be associated with the class membership. We analyzed these potential differences by directly including the covariate as a predictor of between and within class trajectory parameters in the GMM analysis.

Results

RAN letters for probands and affected parents

Latent variable growth mixture models were used to examine the trajectories of RAN Letters row by row for the sample of children who were diagnosed with dyslexia and a sample of their affected parents who also had dyslexia. Based upon the criteria described above, the best fitting models of the number of seconds per row were those that identified two latent classes of trajectories for probands and affected parents. The fit indices for growth mixture models with different numbers of latent classes are shown in Table 2. Two parameters of the trajectories were examined. The first parameter was the initial performance, that is, the number of seconds on average it took the class members to read the first row. The second parameter characterized the shape of the trajectory, that is, whether the

Table 2 Fit indices for growth mixture models with different numbers of latent classes[a] for probands and parents for RAN letters and RAS letters and numbers

Measure and no. of classes	Log *L*	BIC[b]	Entropy	VLMR[b]	Diff in no. of parameters	*P*
RAN letters						
Probands						
1[a]	–1413	2879.436				
2[a]	–1365	2797.975	0.955	52.513	3	0.2947
3[a]	–1363	2811.165	0.975	39.356	3	0.10
Parents						
1	–1413	2879.436				
2	–1365	2797.975	0.955	45.276	3	0.2815
3	–1363	2811.165	0.975	71.785	3	0.0931
RAS letters and numbers						
Probands						
1	–1514	3085.168				
2	–1502	3066.173	0.817	41.656	3	0.0997
3	–1490	3056.342	0.902	24.242	3	0.3103
Parents						
1	–1556	3165.267				
2	–1549	3167.113	0.902	34.143	3	0.2036
3	–1541	3167.357	0.830	15.636	3	0.2189

[a] The model displayed in Figure 1 can be set to abstract 1, 2, or 3 latent factors, each based on the same two indicators—intercept and slope, and then analyze which number of factors provides the best fit to the model

[b] BIC = Bayesian information criterion, VLMR = Vuong-Lo-Mendell-Rubin test

speed with which the subsequent rows were read was increasing, decreasing, or staying the same.

Probands

In the proband sample the "faster" latent class of individuals (n = 111, 91%) performed faster than the smaller class on the first row of RAN (M = 5.06, SE = .18) and on average their speed of reading each of the subsequent four RAN rows *increased* by .7 s per row (M = .71 SE = .11), that is, each row took them longer to read by the average rate of .7 s. The "slower" latent class (n = 11. 9%) took longer than the faster class to read the first row (M = 7.69 s, SE = 1.13) and their reading time for each row *increased* on average by 2.7 s per row (SE = .87). The trajectory of the "faster" latent class was more flat and did not show the large peak on row 3, although row 3 took the most time for both latent classes of probands (see Table 1 and Fig. 2).

Affected parents

The two latent classes of affected parents had a pattern similar to the proband trajectories (Fig. 2). The "faster" latent class (n = 184, 92%) performed faster than the "slower" latent class on the first row of RAN (M = 3.31 s, SE = .10) and on average their reading time for each of the subsequent four RAN rows

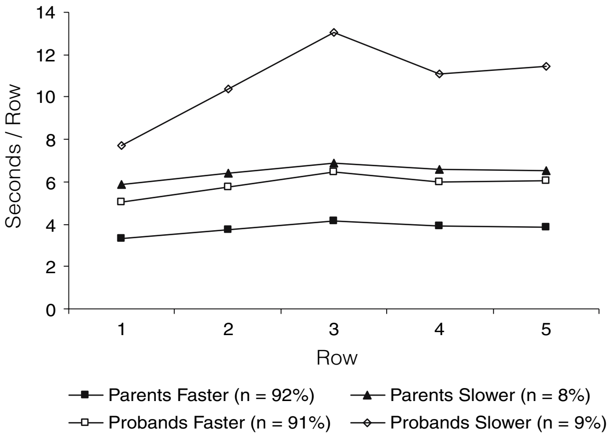

Fig. 2 Estimated growth curves for latent trajectory classes for RAN letters for probands and affected parents

increased by .42 s per row (*SE* = .04). The "slower" latent class (*n* = 15, 8%) took longer to read the first row (*M* = 5.85 s, *SE* = .51) and their speed of reading each row *increased* on average by .53 s a row (*SE* = .55). The main difference between the affected adult latent classes was in their initial scores (3.3 and 5.8 s). The shapes of the trajectories of both latent classes of the affected parents were very similar; the difference between the average rate of change was small.

Comparison of the proband and parent classes

As shown in Fig. 2, the shapes of the trajectories of the affected parents (both the "slower" and the "faster" latent classes) and the "faster" proband latent class were similar. The trajectories of both latent classes in affected parents and the "faster" proband class were fairly flat, with the peak at row 3 much less pronounced than that in the slower proband trajectory. The percentage of the individuals who belonged to the slower latent class was similar between the affected parents (8%) and the probands (9%). The initial level difference (seconds it took to read row 1) between the slower and faster classes was about 2.5 s for both parent and proband classes. However, while the rate at which the performance progressed from row to row was similar for the two affected parent trajectories, it was not for the proband trajectory classes. The "slower" proband latent class took on average almost more than three times longer than the members of the "faster" proband latent class.

RAS letters/numbers for probands and affected parents

Similar to the results for RAN row by row, two reliably different latent classes of probands and affected parents were identified based on their performance on RAS. Table 2 shows the fit indices for growth mixture models with different numbers of latent classes.

Probands

The "faster" latent class of the probands (*n* = 101, 83%) performed faster on the first row of RAS (*M* = 5.62, *SE* = .26) than the "slower" latent class and on average their reading time on each of the subsequent four RAS rows *increased* by .99 s per row (*M* = .00, *SE* = .18). The "slower" proband latent class (*n* = 21, 17%) took longer to read the first row (*M* = 7.10 s, *SE* = .99) and their reading time for each row *increased* on average by 2.73 s per row (*M* = 2.73, *SE* = .58). The trajectory of the "faster" latent class was flatter than that of the "slower" latent class. However, on the RAS trajectories the peak for both latent classes was on row 4, while with the RAN Letters, the peak occurred on row 3.

Affected parents

The "faster" parent latent class (*n* = 186, 93%) performed faster on the first row of the RAS Letters Numbers (*M* = 3.48 s, *SE* = .11) and on average the number of seconds they needed to read each of the subsequent four RAS rows increased by .30 s per row (*M* = .30, *SE* = .03). The "slower" parent latent class (*n* = 13, 7%) took longer to read the first row (*M* = 6.07 s, *SE* = .46) and their speed of reading each row *increased* on average by .22 s a row (*M* = .22, *SE* = .14).

Comparison of the proband and affected parent latent classes on RAS

The shapes of the RAS trajectories of the affected parents (both the "slower" and the "faster" latent classes) and the "faster" proband latent class were similar, that is, they were flatter than the trajectory of the "slower" proband class and had a less pronounced peak. The peak in the RAS trajectories of both probands and parents was located on Row 4 rather than on Row 3 as had been the case with the RAN Letters trajectories. The "slower" parent latent class trajectory for RAS was similar to the "faster" proband trajectory. Seventeen percent of the probands belonged to the "slower" RAS class while 7% of the affected parents were classified as members of the "slower" class. The difference between the RAS initial levels (seconds it took to read row 1) of the "slower" and "faster" classes of parents was 1.48 s and of probands about 2.6 s. The slope of the RAS trajectories was similar for the two parent trajectories, but dissimilar for the probands. The "slower" proband RAS class had a slope 2.8 times greater than the "faster" proband class. The parent and proband trajectories on RAS are shown in Fig. 3.

RAS letters/numbers task results for the typically developing children

Third grade RAS

The "faster" latent class (*n* = 97, 82%) performed faster on the first row of the RAS (M = 5.46 s, SE = .15). On average their speed of reading each of the

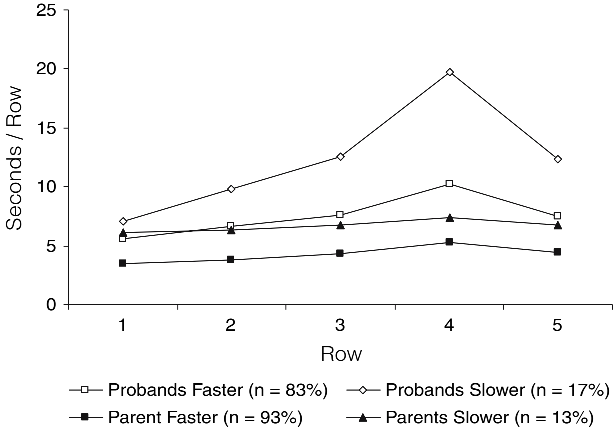

Fig. 3 Estimated growth curves for latent trajectory classes on RAS letters and numbers for probands and affected parents

subsequent four RAN rows increased by .71 s per row ($M = .71$, $SE = .11$). The "slower" latent class ($n = 22$, 18%) took longer to read the first row ($M = 8.35$ s, $SE = .75$) and their rate of reading each row increased on average by 1.60 s per row ($M = 1.60$, $SE = .23$). Both the "faster" and "slower" latent classes showed the Row 4 peak (slower times) that the children with dyslexia and affected parents also had showed (see Fig. 4).

Fifth grade RAS

In the fifth grade ($n = 105$) the "faster" latent class ($n = 101$, 96%) performed faster on the first row of RAS ($M = 4.76$ s, $SE = .15$). On average their time to read each of the subsequent four RAN rows increased by .57 s per row ($M = .568$, $SE = .10$). The "slower" latent class ($n = 4$, 4%) took slightly

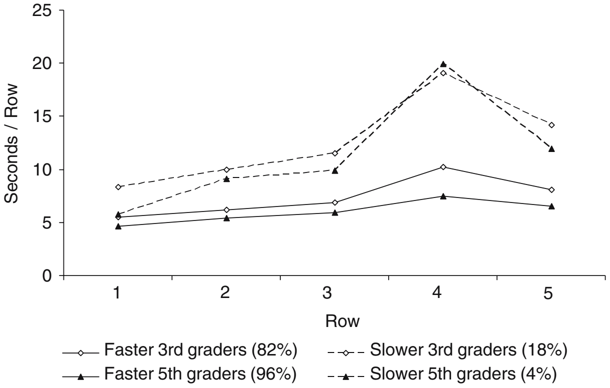

Fig. 4 Estimated growth curves for RAS letters and numbers for typically developing 3rd and 5th graders

longer to read the first row ($M = 5.68$ s, $SE = 1.66$) and their rate of reading each row increased on average by 2.5 s per row ($M = 2.5$, $SE = .69$). Only the "slower" latent class of fifth graders showed the row 4 peak (slower times); the "faster" latent class did not.

Comparison of typically developing and dyslexic children

We compared the children with dyslexia with the typically developing 5th graders because the mean age of the probands was similar to the mean age of the fifth graders who were about 10 months younger on average. The intercept for children with dyslexia and the typically developing 5th graders was statistically significantly different $F(1) = 13.48$, $P < .0001$. Even though the children with dyslexia were somewhat older, and might be expected to be faster, they were slower than the typically developing children in times for the first row, an index of automaticity. This result shows that dyslexics and typically developing readers may differ not only in the mean time for naming the switching letters and digits on a card, based on age or grade norms, but also in the initial time for naming alphanumeric stimuli, that is, automaticity of orthographic-phonological code coordination. In addition, the trajectories were flatter than for dyslexics and only the slower class (4%) showed the peak on row 4. Thus, the typically developing did not appear to have the same difficulty as the children with dyslexia in sustaining the timing of switching orthographic-phonological coordination over time.

Executive function/working memory predictors of RAN/RAS latent classes

These analyses were performed only for the children and adults with dyslexia for whom the predictor measures of executive functions and working memory were available: Delis–Kaplan Color-Word Form Inhibition (Delis, Kaplan, & Kramer, 2001), Delis-Kaplan Verbal Fluency Repetions (Delis et al., 2001), and WJ-R Digits Backwards (Woodcock, & Johnson, 1990). The first measure assesses ability to focus on the relevant dimension and ignore the irrelevant dimension, the second measure assesses ability to self-monitor repetitions in working memory, and the third measure assessed phonological working memory.

RAN

For children with dyslexia, none of these predictor measures of executive function or working memory differentiated between the "faster" and the "slower" latent classes on RAN letters. This finding held whether the predictors were in the GMM model one at the time (total effects) or all at the same time (unique effects). Within the classes, none of the predictor measures was significantly associated with individual differences in intercept or slope for the "faster" class, but Delis–Kaplan Inhibition significantly predicted individual differences in the slope ($z = -2.489$) for individuals in the "slower" latent class, indicating that lower Delis–Kaplan Inhibition scores predicted increases in time over rows among the members of the "slower" class. Thus, for children with dyslexia, an executive function dysfunction (inhibition) is most likely to occur in the class who is slower initially and gets progressively slower over time in sustaining the orthographic-phonological coordination process.

For adults with dyslexia, Delis Kaplan Inhibition and WJ-R Digits Backwards were both statistically significant predictors of the intercept on RAN Letters, that is, the two classes differed significantly on these measures whether the measure was entered by itself (total effects) or together in a model that included three variables (Delis Kaplan Inhibition, Delis–Kaplan Verbal Fluency Repetitions, and WJ-R Digits Backwards). Within the classes of affected adults, after accounting for the differences on these variables between the classes, individual differences among individuals in the "faster" latent class in their intercepts were significantly predicted by Delis Kaplan Inhibition ($z = -3.866$) and WJ-R Numbers Backwards ($z = -3.466$). For affected adults in the "slower" latent class, individual differences in the intercepts were significantly predicted by Delis–Kaplan Inhibition ($z = -2.608$). Thus, for adults with dyslexia, both executive function dysfunction (inhibition) and phonological working memory explained unique variance in both classes of response—those who were initially the slowest and became progressive slower and those who were somewhat faster initially and become slower at a slower rate over time than did the other class.

RAS

For children with dyslexia, none of the predictors differentiated between the latent classes on RAS letters and numbers. Within the latent classes, WJ-R Numbers Reversed significantly accounted for individual differences in slope for children with dyslexia in both the "faster" latent class ($z = -2.709$) and the "slower latent class ($z = 2.195$). For the "faster" latent class, for each unit of increase in working memory scores (the higher the score the better the working memory) the slope decreased (the naming was faster) by .81 of the standard deviation. The Delis Kaplan Verbal Fluency Repetitions significantly predicted individual differences in the intercept within the "slower" latent class ($z = -3.068$). For each unit of decrease in the Delis Kaplan Verbal Fluency Repetitions, the intercept increased by .66 of SD. This result suggests that better self-monitoring, an executive function, was associated with better initial automatic orthographic-phonological code coordination.

For adults with dyslexia, Delis Kaplan Inhibition and WJ-R Numbers Backwards, when entered one at the time (total effects), were both significant predictors of RAS letters and numbers and differentiated between the classes on both the intercept and the slope. When all predictors were in the model, Delis Kaplan Inhibition remained significantly different between the two latent classes and predicted the intercept and the slope. In addition, WJ-R

Numbers Backwards was a significant unique predictor of the slope. Within class, WJ-R Numbers Backwards significantly predicted the slope of the "faster" latent class; and Delis–Kaplan Inhibition significantly predicted both the intercept ($z = -4.524$) and slope ($z = -2.101$) of the "faster" latent class and the intercept ($z = -2.295$) within the "slower" latent class.

Summary and conclusion

When measures of executive function (inhibition and verbal fluency) and phonological working memory were included as a set of predictors in the model for children, none differentiated between latent classes for RAN letters or RAS letters and numbers. However, Delis Kaplan Inhibition predicted individual differences in RAN letters slope within the slower latent class in children. When measures of executive function (inhibition and verbal fluency) and phonological working memory were included as a set of predictors in the model for adults, Delis Kaplan Inhibition uniquely differentiated latent classes on both intercept and slope of RAS and WJ-R Digits backwards uniquely differentiated latent classes on RAS slope. Collectively, these results support the contribution of executive functions and working memory to performance on RAN and RAS tasks, consistent with arguments put forth by Wolf and Bowers (1999) about the complexity of processing requirements for these tasks that are not purely phonological tasks. Executive functions and working memory were more likely to differentiate classes of response related to timing in adults than in children.

Discussion

Results of the growth mixture modeling showed that a 2-factor model based on intercept and slope identified two classes of responders on RAN and RAS timed row by row (10 symbols per row across five sequential rows) in children and adults with dyslexia. These dyslexics were on average significantly impaired in RAN and RAS, which were hypothesized to reflect phonological loop and executive functions of verbal working memory, respectively. Thus, the first research hypothesis was confirmed—there were individual differences in the trajectories for naming times across rows. The second research hypothesis was also confirmed—these individual differences in trajectories were also observed in typically developing students; however, differences between children with and without dyslexia emerged in the 10–11 year-old range. The third research hypothesis also received support in that executive functions and/or phonological working memory predicted initial and/or sustained naming time for children and adults with dyslexia.

These classes of naming times across rows differed in temporal coordination of orthographic and phonological stimuli at intercept in children and adults and in slope in children. For the slowest class of children and both classes of adults, executive functions predicted the slope, which reflects changes in the orthographic-phonological coordination process over time. Not only the RAN and RAS tasks themselves but also the intercept and slope within each of these tasks may assess the phonological loop and executive functions of working memory, respectively.

The *intercept* for row 1 may reflect automatic coordination of orthographic codes (letters or letters and numerals) and phonological name codes (segmental phonemes and supra-segmental intonational contours), a phonological loop function. Such automatic coordination requires inhibition of irrelevant name codes activated in working memory for prior orthographic symbols and activated in long term memory while accessing the currently relevant name code. Latent classes differed in the initial intercept. The intercepts for children with dyslexia and the typically developing 5th graders were also statistically significantly different in this initial intercept, with the somewhat older dyslexics performing more slowly than the younger typically developing students. Taken together, these results suggest that dyslexics in general are slower in automatic retrieval than good readers and some dyslexics are even slower than others in automatic retrieval. Both impaired inhibition and working memory may contribute to the problems in automatic retrieval of phonological name codes for orthographic codes in children (but neither of these processes contributes uniquely). Both impaired inhibition and working memory may contribute to the problems in automatic switching during retrieval of phonological name codes for orthographic codes in adults, but inhibition contributes uniquely to intercept.

Increases in time in *slope* across four subsequent rows may reflect extra demands placed on the executive functions of working memory in dyslexics for controlled, strategic processing sustained over time while searching repeatedly through long term memory for name codes for orthographic codes. Despite practice on earlier rows, children and adults with dyslexia (in both latent classes) got slower rather than faster over time across rows. One interpretation of this finding is that it is difficult for dyslexics to sustain mental effort over small intervals of time for rapidly retrieving familiar names for orthographic symbols. This impairment in sustaining mental effort in speeded retrieval of names codes for orthographic symbols is an “invisible disorder”, not observable unless an individually administered test is given on which times are recorded for naming symbols on each of five sequential rows. An alternative interpretation is that dyslexics habituate to repetitive tasks not involving novel stimuli more quickly than do good readers. This habituation renders dyslexics less responsive to new orthographic symbols that appear across rows. Yet another explanation is that inhibition is impaired by accumulating name codes from prior trials, making it more difficult to focus on the relevant name at the moment for the most immediate orthographic symbol when executing a controlled, strategic search for it in long term memory. The peak in naming time on row 3 on RAN but row 4 on RAS may provide support for the latter explanation. Because RAS generates fewer name codes within a category than does RAN, it likely takes longer for the accumulating name codes to interfere with inhibition on RAS than on RAN. It is also possible that the three alternative explanations are not competing explanations but rather contribute jointly to explain the slower naming times over time in the dyslexics.

The results of this study illuminate the challenges facing dyslexics. Dyslexics may be not only slower overall on RAN and RAS tasks than good readers but also they may show individual differences in relative ability for the *separable processes of phonological loop function* early in processing (the intercept) and sustained executive processes for *strategic controlled coordinating of orthographic and phonological codes repeatedly over time* (the slope). Executive functions (inhibiting and self-monitoring/updating) and phonological working memory may contribute to both the automatic retrieval and sustained mental effort for controlled searches involved in mapping phonological codes onto orthographic codes. Thus, even when the decoding problems of children with dyslexia improve because they have learned to coordinate the phonological, orthographic, and morphological codes in working memory, they may have persisting problems with other working memory components (phonological loop or executive functions) that interfere with development of reading and/or writing fluency. The impaired automatic functioning of the phonological loop and executive functions involved in sustained processing may be an ‘‘invisible’’ disability that makes it more difficult for dyslexics to initiate or sustain written language activities unless documented through assessment and treated through specialized instruction.

The results also suggest issues for future research. In studies of response to intervention (RTI), researchers might investigate whether slower or faster latent classes on a RAN or RAS task across five rows significantly predict the slower and faster responders to instruction. It may turn out that it is as important to assess rate over mini-segments (e.g., five time points close in time) as it is in larger stretches of time (beginning, middle, and end of the school year). The mini-segments may provide insight into the processing problems that make it difficult for students with dyslexia to initiate or sustain written language learning. The longer segments allow tracking of progress on achievement measures. The results reported here generalize only to dyslexics with spared verbal comprehension (see introduction). Further research is need to evaluate whether these findings generalize to students with language learning disability discussed in the introduction as well.

Regardless of what new research these results might stimulate, they do provide support for Wolf and Bower's (1999) contention that there is a second deficit in developmental dyslexia beyond the phonological core deficit. This second core deficit cannot be explained solely on the basis of phonological processing. Rather, it appears to reflect an impairment of initial timing in naming orthographic symbols and/or sustained naming of orthographic symbols over time.

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