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Novel Reading Index for Identifying Disordered Reading Skill Development: A Preliminary Study

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Abstract

Children with ADHD are at high risk of developing a Reading Disability (RD), though the reasons remain unclear. ADHD-associated impairments, including processing speed, can complicate clinical evaluation for a co-occurring RD diagnosis. We propose a novel metric to (i) assess reading development and (ii) provide an alternative method to classifying readers that may aid investigations for etiologies of RD in ADHD. Specifically, as both phonological decoding and word recognition skills are important precursors of reading fluency, we propose a new quantitative method comparing these skills after accounting for variations in perception, motor response, or processing speeds. Forty boys (14 control, 15 ADHD, 11 ADHD/+RD) completed a lexical decision task testing decoding and another assessing word recognition. Response time data was modeled using a Drift Diffusion approach to estimate the underlying reading skills. Using these reading skill estimates, we calculated a novel Reading Tendency Index and classified participants into three reading groups (Decoders, Balanced Readers, and Sight Readers). The reading and cognitive performance of these groups were consistent with theoretical predictions and subsequently provided external validity for the novel Reading Tendency Index classification. Our findings demonstrate a potential classification tool for readers based on individual's developed, reading tendencies.

Introduction

A co-occurring Reading Disability (RD) diagnosis is given to 45 % of children with Attention Deficit/Hyperactivity Disorder (ADHD, Del’Homme, Kim, Loo, Yang, & Smalley, 2007; DuPaul, Gormley, & Laracy, 2013; Pennington, Groisser, & Welsh, 1993; Willcutt & Pennington, 2000; Yoshimasu et al., 2010). Similarly, evidence has shown that children with ADHD are at greater risk for impaired reading fluency overall (Cutting, Koth, Mahone, & Denckla, 2003), suggesting that abnormal reading development may occur in ADHD, even without a formal RD diagnosis. Over the past 30 years, the understanding of children with RD has grown substantially from the perspective of behavior, cognition, and neurobiology (e.g., Fletcher et al., 2002). Current criteria for normal reading or RD depend on standardized assessment and often focus on an individual’s ability to decode words (phonological ability, Baron & Strawson, 1976; Boder, 1970; Price et al., 2003; Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Stanovich, 1988; Wang, Marinus, Nickels, & Castles, 2014). However, much less is firmly established about how ADHD-related impairments may influence basic reading processes, making it unclear whether the assessment procedures in classifying children with RD and guiding appropriate interventions are maximally effective (e.g., Eden & Vaidya, 2008). The aim of the current study is to introduce the concept and method for a dynamic, quantitative metric characterizing readers grounded in dual-route theory (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and based on observable linguistic behavior (Uppstad & Tønnessen, 2007), which we call the Reading Tendency Index. The ultimate purpose of this index is to inform intervention strategy choice through identifying the individual’s standard approach to single word reading, regardless of whether an individual meets an arbitrary cut-off designating a disability in a particular reading skill.

Fluent reading develops through many stages, chiefly including the progression from decoding to recognizing words, and can be predicted by naming speed and phonemic awareness assessments (Norton, Beach, and Gabrieli, 2015). Decoding skills, involving the phonological process of converting graphemes to phonemes, are a central foundation for early reading ability (Carreiras, Armstrong, Perea, & Frost, 2014). Proficiency in word recognition, which follows the learned decoding skills, is a critical next step in developing reading fluency (Sela, Izzetoglu, Izzetoglu, & Onaral, 2012). Numerous investigations to identify new diagnostic criteria have focused on classifying readers based on poor decoding ability or poor word recognition ability, suggesting that significant deficits in one skill will lead to dependence on the other (Baron & Strawson, 1976; Sprenger-Charolles et al., 2000; Stanovich, 1988; Yap, Sibley, Balota, Ratcliff, & Rueckl, 2014). The classifications often are divided between essentially (i) sight readers who do not have strong decoding and are conceptually similar to “phonological dyslexics” (Castles and Coltheart, 1993), “dysphonetic readers” (Boder, 1970), or “Chinese readers” (Baron & Strawson, 1976), and (ii) decoders who are unable to acquire strong word recognition and are similar to “surface dyslexics” (Castles and Coltheart, 1993), “dyseidtic readers” (Boder, 1970), or “Phoenician readers” (Baron & Strawson, 1976). As these classifications based on decoding or word recognition deficits suggest, the dual-route theory for reading development provides a unifying, neuroscientific perspective (Coltheart et. al, 2001). Briefly, within this framework,

decoding is handled by a dorsal neural network, or “route”, involving the posterior superior temporal gyrus, inferior parietal lobe, and inferior frontal gyrus. Word recognition is mediated by a ventral network comprised of the superior temporal gyrus, and inferior frontal gyrus (for review, Hickok and Poeppel, 2004). Subsequently, different manifestations of RD may be related to altered structure or function in one route or the other. This study capitalizes on these theoretical, developmental underpinning by introducing a novel, quantitative, head-to-head comparison of the skills associated with each route, which we call the Reading Tendency Index.

In addition to phonological processing and naming speed, reading skill acquisition and the mastery of both decoding and word recognition depends on the maturation of different cognitive domains, such as working memory, cognitive flexibility, and attention (Alloway, Gathercole, & Elliott, 2010; Carreiras et al., 2014; Christopher et al., 2012; Horowitz-Kraus, 2013; Sela et al., 2012; Sesma, Mahone, Levine, Eason, & Cutting, 2009). Individuals with both ADHD and RD or ADHD alone have shown shared and unique patterns of cognitive impairments in different domains (Christopher et al., 2012; McGrath et al., 2011; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), which may uniquely impact the development of core reading abilities leading to compromised performance on reading fluency (Benjamin & Gaab, 2012; Bental & Tirosh, 2007; Katzir et al., 2006). Thus, the ability to differentiate individuals who rely on word recognition, or tend to guess words over sounding them out, in single word reading may provide powerful insights into the etiology frequently co-occurring psychiatric disorders such as ADHD and RD (Del’Homme, Kim, Loo, Yang, & Smalley, 2007; DuPaul, Gormley, & Laracy, 2013; Pennington, Groisser, & Welsh, 1993; Willcutt & Pennington, 2000; Yoshimasu et al., 2010).

Numerous studies have used lexical decision tasks to generate response time data that can be modeled with the Drift Diffusion Model (DDM; e.g., Ratcliff & McKoon, 2008; Ratcliff, Gomez, & McKoon, 2004a; Ratcliff, Perea, Colangelo, & Buchanan, 2004b). Using the DDM is important for determining individuals’ underlying decoding and word recognition abilities in clinical populations, since the confounding effects of processing speed, attentiveness, or motor speed variations are addressed in the mathematical model (Philiastides, Auksztulewicz, Heekeren, & Blankenburg, 2011; Ratcliff et al., 2004b). Bogacz and colleagues (2006) provide an in-depth explanation and evaluation of the model, which uses $dx = A dt + cdW$, $x(0) = 0$ to describe how noisy evidence for or against a hypothesis is integrated over time and is governed by a speed-accuracy tradeoff (Ratcliff, 1978). In short, dx is the amount of progress toward a decision boundary that is made in a small segment of time, dx , with cdW as a noise term and $x(0) = 0$ representing an initially unbiased choice. The drift rate (A) reflects how quickly evidence is accumulated to make a choice and has been interpreted as estimating underlying cognitive abilities in domains required for the choice (see Bogacz, 2006 for examples across domains). Drift rate varies by individual and is the most salient term for this study. In this study, we calculate each individual’s drift rate for decoding from one lexical decision and the word recognition drift rate from another lexical decision task. By comparing the relative proficiency in decoding versus word recognition head-to-head, we introduce a simple and novel assessment metric called the Reading Tendency Index that characterizes the individual’s intrinsic preferred approach for single word reading.

Based on a previously recruited sample of typically developed children and adolescents as well as age-matched ADHD individuals with and without RD, we postulated that the implementation of this RTI could identify three distinct groups for word reading: Balanced Readers (ability in both decoding and word recognition), Decoders (relatively poorer in word recognition ability), and Sight Readers (relatively poorer in word decoding ability). Additionally, because of the dependency of core reading domains on cognition, we hypothesized that readers with a tendency to decode words (Decoders) would have poorer cognitive flexibility, which is needed to execute a switch to a more efficient reading strategy (Colé, Duncan, & Blaye, 2014). Readers that depend on word recognition (Sight Readers) will have poorer decoding skills, verbal working memory, and cognitive flexibility. In all, this study introduces a potentially useful classification tool and begins to suggest better targeted instructional remediation methods may need to be considered and investigated, especially for individuals with ADHD and poor reading ability.

Methods

Participants

Participants were originally recruited through community-based advertisement and clinical referrals for an fMRI study (closed enrollment) to investigate neural differences between ADHD and TDC. Because ADHD is more prevalent in boys (Willcutt, 2012), 14 ADHD/-RD, 11 ADHD/+RD, and 15 typically developing control (TDC) boys between the ages of 9 and 16 years of age from the Detroit (Michigan) and Windsor (Ontario) metropolitan areas with English as their first and primary language were enrolled. Exclusion criteria for all groups included history of head injury resulting in loss of consciousness, Full Scale IQ (FSIQ) less than 80, a first-degree relative with a past or present diagnosis of a major DSM-IV disorder including schizophrenia, pervasive developmental disorders, tic disorders, eating disorders, or mood disorders. ADHD participants with a comorbid oppositional defiant disorder, conduct disorder, or anxiety disorder were included. All participants were free of psychostimulant medication for at least a 24-hour period prior to the reading assessment and the fMRI scan that provided the behavioral data. Although six participants reported left-handedness, left-hemispheric language dominance was confirmed for all participants through inspection of first-level activations in response to a reading fMRI task. Following a complete description of the study, written informed consent was obtained from the parents or guardians as well as assent from the child. The Wayne State University Institutional Review Board approved the study protocol and consent.

Diagnosis

ADHD status based on the DSM-IV-TR criteria was determined for all participants through a semi-structured, diagnostic interview using the Kiddie Schedule of Affective Disorders - Present and Lifetime (K-SADS-PL, Kaufman et al., 1997) given by our clinical neuropsychologists. The Disruptive Behavior Disorders Scale (DBD) and Iowa Conners Hyperactivity/Impulsivity Scale questionnaires were also given to the parent/guardian and the subject's teacher to provide supplementary data about ADHD symptomatology and comorbid conduct disorders.

To characterize RD, the Word Reading, Pseudoword Decoding, and Spelling subtests of the Wechsler Individual Achievement Test - III battery (WIAT-III; PsychCorp, Pearson Education; San Antonio, TX) were administered. To calculate an Achievement-Aptitude Discrepancy a Full Scale IQ (FSIQ) score was also obtained using the Wechsler Abbreviated Scale of Intelligence (WASI; PsychCorp, Pearson Education; San Antonio, TX). Since the discrepancy model has received criticism for identifying individuals with RD (e.g., Fletcher, Francis, Rourke, Shaywitz, & Shaywitz, 1992; Uppstad & Tønnessen, 2007), a more stringent, significant discrepancy ($p = .01$) per the WIAT-III Achievement-Aptitude Discrepancy tables in at least two of the three reading subtests was used as an operational definition of RD. None of the TDC met criteria for RD.

Materials: Lexical Decision Tasks

The behavioral data assessing basic reading processes were collected during an fMRI study, which incorporated two lexical decision tasks (LDT, e.g., Ratcliff, 1978) as consecutive, block design fMRI paradigms. One LDT biased phonological decoding by using only pseudowords (e.g., “glunk”) or less common real words (e.g., “choir”) as stimuli. The other LDT bias word recognition by using letter strings (e.g., “jnwk”) or common real words (e.g., “cat”). Details of each task follows, but for both, participants were instructed to do their best to identify whether each stimulus was a word or not. Responses for the pseudoword and high-frequency word trials were the primary outcomes to calculate drift rates for the basic reading skills, as elaborated in the section entitled “Drift diffusion modeling”.

The stimuli were obtained from the English Lexicon Project (Balota et al., 2007), which characterizes words using several linguistic features, including the Hyperspace Analogue to Language estimates (HAL, Lund & Burgess, 1996) to rank word frequency in print. Stimuli and responses were controlled by Presentation® software (v15.0, www.neurobs.com). Lower case stimuli were presented as white, 112 point Arial font text on a gray background viewed through a mirror above the subject’s head during an fMRI scan. During rest blocks, a series of pound signs were displayed (i.e., “###”). Reaction times (RT) were recorded using a two-button response box in the subject’s right hand with words always requiring a response with the index finger and nonwords with the middle finger.

The phonologic lexical decision task (pLDT) had twelve, pseudorandomized task blocks (duration = 18 sec) followed by a 14 sec rest block and resulting in a 5 min 42 sec task. Task blocks required participants to distinguish low frequency words (mean log HAL = 8.4, HAL range = 6.6 – 9.6, 28 total trials) from pseudowords (56 total trials), which requires phonological decoding (Zeguers et al., 2011). Low frequency words and pseudowords were 3–5 letters in length. Pseudowords were legal, pronounceable combinations of graphemes, but were not pseudohomophones (e.g., “bair”). To decrease the likelihood of correctly guessing by chance, the percentage of pseudowords varied from 30–70% of the stimuli in each block. Mean bigram frequency did not differ between blocks. Stimuli were presented for 1.6 sec with an interstimulus interval of 2.25 sec., corresponding with approximately 38 words per minute. This rate is much slower than the 140+ words per minute estimate of fluent reading in upper elementary (c.f., Kuhn & Stahl, 2003).

During the Orthographic Lexical Decision Task (oLDT), thirteen task blocks of 18–20 sec. each and nine rest blocks of 14 sec. each were interspersed for a total paradigm of 6 min 35 sec. Word recognition abilities were assessed through the rapid identification of high-frequency words (mean log HAL = 11.8, HAL range = 10.0 – 15.0, 92 trials) and consonant strings (83 trials). Each task block contained a mix of eight monosyllabic, high-frequency words and consonant strings. Seven blocks were predominately high-frequency words (80%) and the other six blocks were mostly consonant strings (80%). The stimuli were presented twice as fast with the stimulus duration = 0.8 sec and the interstimulus interval = 1.2 sec than in the pLDT to promote rapid word recognition, rather than more laborious decoding processes. Despite the increased pace, the effective reading rate remained at 75 words per minute, well within the accessible range even for disabled readers.

Drift diffusion modeling

Drift rates from the two, different lexical decision tasks were calculated using the Java-based, EZ-diffusion applet (Wagenmakers, van der Maas, & Grasman, 2007) by inputting mean RT, RT variance, and proportion correct data. EZ-diffusion modeling is a simplified, six parameter version of DDM, which accommodates data with too few errors for a proper error RT distribution, precluding a full DDM (Wagenmakers et al., 2007). EZ-diffusion has similar assumptions as DDM, including a right-skewed distribution of RTs. To test the normality of RT distributions, the standard errors of skewness for pseudoword RTs (from the pLDT) and high-frequency word RTs (from the oLDT) were calculated and converted to a Z-score. Since the number of observations is large, the approximation for standard error of skewness, $(6/n)$, was appropriate. Both pseudoword RT ($Z = 15.7$) and high-frequency word RT ($Z = 24.7$) distributions were right-skewed, depicted in Fig. 1. Therefore, individual subject scores for the drift rate, non-decision time, and boundary separation were calculated for both decoding (pseudoword RT) and word recognition (high-frequency word RT).

Reading Tendency Index calculations

The goal of the RTI was to predict individual's consistent approach to single word reading quantitatively. To calculate the RTI score, each reader's decoding drift rate was subtracted from the word recognition drift rate, resulting in a single index score. A strongly dominant or more proficient skill (i.e., greater drift rate) is reflected by a greater difference from zero (Fig. 3). Specifically, a negative index value indicates greater skills at decoding strategies relative to word recognition ability, while a positive index value corresponds with greater ability in word recognition skills relative to decoding skills. An Index value near zero indicates balanced skills in both decoding and word recognition. Going forward, the hypothesis is that individuals with a strength in one skill relative to the other (i.e., scores further from zero) will have a greater tendency to use the stronger approach for single word reading, strengthening related neural circuitry (Philiastides, 2011). Given that this is a small preliminary study, group membership for tendency-based analyses was determined by tertiles with the middle tertile being anchored around zero and reflecting strengths in both decoding and word recognition. The three resulting groups were: individuals with similar decoding and recognition skills and no propensity (Balanced Readers), and two groups which had a propensity to rely on either phonological decoding skills (Decoders) or on word recognition skills (Sight Readers).

Assessment of related cognitive skills

Verbal working memory and cognitive flexibility are both important for skilled reading. To assess verbal working memory using a sentence span memory test (Rourke & Orr, 1977), participants listened to and then repeated grammatically correct sentences, which progressed in word number and phrase complexity. Sentences were considered correct if repeated verbatim on the first attempt with allowance for logical article or small preposition substitutions (e.g., “a” instead of “the”). The assessment was discontinued after three consecutive sentences containing errors. To assess cognitive flexibility, Intra-/Extra-Dimensional Set Shifting (IED) from the Cambridge Neuropsychological Test Automated Battery was completed. IED Shifting is a seven-minute test similar to the Wisconsin Card Sorting Test wherein participants must learn categorization rules that are subsequently changed within a dimension (e.g., color) or between dimensions (e.g., shape). Outcomes include total trials to learn the rules and total errors. Five participants (2 TDC, 2 ADHD/-RD, and 1 ADHD/+RD) had missing IED assessments due to software license or technical issues.

Statistical Analysis

Group differences between all three groups regarding age, FSIQ, normed scores for the WIAT-III Word Reading, Pseudoword Decoding, and Spelling subtests were assessed with ANOVA. Group differences for both the pseudoword drift rate and word recognition drift rate were also investigated using ANCOVA, with age as the covariate, to supplement the reading skill characterization. Similarly, IED Shifting Total Trials-Adjusted and Errors (cognitive flexibility) and Sentence Span Completed Items (verbal working memory) were evaluated by ANCOVA (age).

To assess specifically whether differences between RTI-based groups could be explained by the redistribution of ADHD/+RD and ADHD/-RD between the groups, participants were compared across demographic and reading skill dimensions in a secondary analysis with ADHD and RD diagnosis as the main effect. Differences between TDC, ADHD/+RD, and ADHD/-RD were assessed using ANOVA for Conners' Inattentive/Cognitive Problems, Conners' Hyperactivity subscales, age, and FSIQ. Tukey's HSD *post-hoc* tests were performed for all main effects reaching $p < .05$. All statistics were modeled using JMP version 11 (SAS; Cary, NC).

Results

Demographics of Reading Tendency-based and RD-based groups

Table 2 provides summaries of the group membership according to the RTI or ADHD/RD status. The Balanced Readers were composed of nine TDC and only five of the ADHD/-RD (3 Combined; 2 Inattentive). The Decoders included three TDC, five ADHD/-RD (3 Combined; 2 Inattentive), and six ADHD/+RD (5 Combined; 1 Inattentive). Of the Decoders with ADHD, two had a Conduct Disorder secondary diagnosis and one had generalized anxiety. The thirteen Sight Readers were four TDC, four ADHD/-RD (all combined), and five ADHD/+RD (2 Combined; 3 Inattentive). Of the Sight Readers with ADHD, two had a Conduct Disorder secondary diagnosis. The three reading tendency groups did not differ

with respect to age ($F_{2,39} = 0.67$; $p = .51$) or FSIQ ($F_{2,39} = 2.18$; $p = .13$). For completeness, groups based on diagnosis of ADHD with or without RD were compared and did not differ with respect to age ($F_{2,39} = 0.96$; $p = .39$) or FSIQ ($F_{2,39} = 0.78$; $p = .46$).

ADHD symptoms and RD assessments

The Conners' Inattention/Cognitive Problems subscale differed between the reading tendency groups ($F_{2,39} = 6.3$; $p = .004$), but Hyperactivity did not ($F_{2,39} = 2.5$; $p = .09$). The Tukey's HSD post-hoc test revealed that Sight Readers had significantly greater inattentive symptoms than Balanced Readers ($p = .003$; Cohen's $d = 1.3$). Additionally, Sight Readers tended to have greater inattentive symptoms than Decoders, but the difference failed to reach significance ($p = .09$; Cohen's $d = .73$).

Reading tendency-based group differences were evident on WIAT-III Word Reading ($F_{2,39} = 6.5$; $p = .004$) and Spelling subtests ($F_{2,39} = 4.2$; $p = .019$). Sight Readers had lower achievement scores on both measures compared with Balanced Readers (Tukey's HSD post-hoc Word Reading $p = .004$, Cohen's $d = 1.09$; Spelling, $p = .015$, Cohen's $d = 1.1$). Sight Readers had lower achievement than Decoders on WIAT-III Word Reading (Tukey's HSD, $p = .027$, Cohen's $d = .70$), but not Spelling (Tukey's HSD, $p = .15$, Cohen's $d = .70$). WIAT-III Pseudoword Decoding was not significantly different between reading tendency groups ($F_{2,39} = 2.7$; $p = .054$). Table 3 provides detailed scores for the comparisons.

Cognitive assessments

Regarding verbal working memory, the reading tendency groups differed on sentence span ($F_{2,39} = 5.9$; $p = .006$) with Sight Readers performing poorly compared to Balanced Readers (Tukey's HSD, $p = .007$, Cohen's $d = 1.0$) and Decoders (Tukey's HSD, $p = .031$, Cohen's $d = .9$). Cognitive flexibility, measured by IED Shifting, showed tendency-based group differences in Total Trials - adjusted ($F_{2,35} = 7.1$; $p = .003$) and Total Errors ($F_{3,38} = 6.0$; $p = .006$). Sight Readers attempted significantly more IED trials and committed significantly more errors compared to Balanced Readers ($p = .002$, Cohen's $d = 1.6$ and $p = .004$, Cohen's $d = 1.5$, respectively). The Tukey's HSD post-hoc tests did not reach significance between Balanced Readers and Decoders.

Discussion

A strong foundation of learning decoding skills and, then, acquiring word recognition skills is essential for developing reading fluency. The goal of this preliminary study, involving TDC, ADHD/-RD, and ADHD/+RD boys, was to introduce a quick and powerful, automated metric to identify whether an individual, particularly with ADHD, has developed decoding and word recognition skills in tandem. The main finding is that three groups of readers—Balanced Readers, Decoders, and Sight Readers—with distinct reading skill and cognitive profiles could be identified using this novel metric, which we called the Reading Tendency Index. Additionally, we found that boys with ADHD were more likely to be classified as either Decoders or Sight Readers than Balanced Readers. These findings are consistent with other studies showing that children and youth with ADHD are at greater risk than the general population for decreased overall reading fluency (Cutting, Koth, Mahone, &

Denckla, 2003). Further, our findings provide support that underlying cognitive impairments associated with ADHD may decrease the likelihood of successful mastery of either decoding or word recognition skills (Christopher et al., 2012; Horowitz-Kraus, 2013; Sela et al., 2012). Our novel Reading Tendency Index assesses reading skills after accounting for these impairments, potentially providing a tool to predict individual's reading abilities independent of co-occurring ADHD status and guide intervention strategies.

This newly introduced Reading Tendency Index is grounded in the dual-route theory of reading (Coltheart et. al, 2001) and compares decoding and word recognition skills head-to-head, based on response times during two lexical decision tasks. The resulting Index score lies on a continuum from heavily favored decoding (i.e., "Decoders") to balanced use of both skills or, even, to dependence on word recognition (i.e., "Sight Readers"). For this study, statistical tertiles delineated the three groups, Balanced Readers, Decoders, and Sight Readers. Examining the reading performance and associated cognitive skills (Table 4) revealed that Balanced Readers showed the greatest overall reading outcomes and cognitive scores, as predicted. Decoders demonstrated weaknesses in word recognition relative to both other groups and tended to have less cognitive flexibility compared to Balanced Readers. Decreased cognitive flexibility in Decoders is consistent with ADHD symptomatology and with developing a tendency – these readers regularly use a single strategy to accomplish single word reading to the detriment of developing the other skill (i.e., word recognition.) Sight Readers also evidenced lower cognitive flexibility in addition to poorer verbal working memory. These findings are in line with the developmental framework for reading fluency and other studies showing that relying on word recognition is an indicator for poor growth potential toward reading fluency (Deacon, Benere, & Castles, 2012; McNorgan, Alvarez, Bhullar, Gayda, & Booth, 2011; Sprenger-Charolles et al., 2000; Talcott, Witton, & Stein, 2013). An overview of the conceptual framework for the cognitive abilities or impairments associated with each reading group is available in Table 1.

Based on their scores from the novel Index proposed in the current study, 84% of the participants with ADHD were classified as having sub-optimal reading strategies (i.e., an extreme tendency in either direction) compared to 44% when based on RD diagnosis status. Individuals with ADHD display various combinations of impaired function in the cognitive domains identified as influencing reading development (Table 1). As the decoding and word recognition tendencies have different, neural implications based on the dual-route theory, we speculate that functional neuroimaging of ADHD/-RD and ADHD/+RD may be confounded by a mixture of Decoders and Sight Readers in each diagnostic group. This framework provides a possible explanation for how heterogeneity in ADHD has limited the search for common etiologies in ADHD and RD studies (Bental & Tirosh, 2007; Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Katzir et al., 2006; Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005; Willcutt et al., 2005). Furthermore, of those diagnosed with co-occurring ADHD/+RD in our study, half were categorized as relying heavily on decoding and the other half on word recognition. The split between tendencies was somewhat unexpected, as traditionally, children with RD have deficits in phonological processing. This finding underscores the need for describing readers using a quantitative approach (i.e., the Reading Tendency Index) that accounts for common individual differences, including processing speed and variable response time. This example of several children with ADHD/+RD, but a

Decoder profile, also demonstrates the potentially profound implication of using the Reading Tendency Index to guide intervention strategies. Instead of more phonological remediation, these readers may need training in visual working memory, cognitive flexibility, or other skills supporting word recognition.

Overall, the Reading Tendency Index provides an assessment of learned decoding and word recognition skills in a concise, quantitative metric that can be communicated positively with educators and guardians, as well as the child. The Index score reflects relative strengths in the basic reading skills, which also directly informs interventionists where to focus their efforts for the individual child. Another major advantage of the Index is that individual differences in processing speed, which often confound reaction time-based comparisons in ADHD or RD studies (Katz, Brown, Roth, & Beers, 2011; Shanahan et al., 2006; Tamm et al., 2014), are accounted for in the EZ-diffusion modeling. Also, the presence of an extreme tendency corresponded with less cognitive flexibility, potentially indicating that the child locks into a specific approach that works without being able to switch easily to the other approach. Ultimately, this lack of cognitive flexibility inhibits the child's reading development, as the child does not switch to the more efficacious skill, whether for time (word recognition) or novelty (decoding). Thus, future studies may benefit from using the Reading Tendency Index to examine the etiology of reading problems. Lastly, if implemented similarly to this study, the Index can be calculated from about ten minutes of computerized lexical decision tasks, providing a potentially broad-reaching and affordable screening mechanism that can be readily implemented in the school. As a screening tool, the RTI would also avoid time and financial losses associated with a "wait to fail" model that also requires a formal psychoeducational assessment.

Despite the promise of the new Index, some limitations of this study need to be addressed in future studies. We anticipate including a true RD group, which was not represented in this study, would help delineate cognitive differences leading to the reading tendency subtypes. The small sample of only boys resulted in the need to use tertiles based on the Index scores to define the groups. While the tertile approach showed considerable power in distinguishing reading performance and associated cognitive profiles, it is unclear whether a larger, more representative sample size of children with fewer ADHD participants would produce as clear of a delineation. Additionally, it is unclear whether the presence of a psychiatric co-morbidity in our ADHD participants influenced the outcome measures or whether the methodology extends to more transparent or deeper orthographies. Future studies should address the discontinuous nature of the Index (i.e., Decoders less than zero, Balanced Readers near zero, and Sight Readers greater than zero), perhaps by adapting machine learning approaches. Future studies should also confirm the findings while performing the paradigms outside the MR scanner, such as in a school, to ensure that the scanner noise or environment did not contribute to poorer performance for some participants. EZ-diffusion modeling uses simplified assumptions, in lieu of more computationally intense drift diffusion modeling, to estimate the reading skills (Wagenmakers et al., 2007). More difficult lexical decision task stimuli may induce higher error rates needed for more rigorous drift diffusion modeling that may also provide a greater separation of reading abilities. Lastly, the predictive ability of the Index should be compared to other known predictors, such as naming speed and phonological awareness (Norton, Beach, and Gabrieli, 2015).

In conclusion, the novel Index reflects an individual's relative decoding and word recognition skills in order to predict which skill(s) should be the focus of remediation. Furthermore, certain cognitive impairments can be hypothesized to contribute to the types of readers identified with the Index (Table 1). Greater understanding of the collection of cognitive impairments associated with specific types of readers may help individualize educational interventions to an even greater extent than is currently available and feasible. Additionally, the Index may be a powerful method of prognosis for developing reading fluency, as Decoders may be delayed in acquiring reading skills (Talcott et al., 2013), while Sight Readers may be unable to make substantial reading gains entirely (Deacon et al., 2012; McNorgan et al., 2011). More work with a larger and more representative sample of school children is needed to verify and extend the utility of the Reading Tendency Index. This is, however, a significant first step towards understanding and quantifying how skilled and non-skilled readers approach single word reading and may also predict correlates within neurobiological network models of reading.

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Fig. 1.

The distributions of the reaction times for both lexical decision tasks are right skewed with numerous outliers. While these distributions are problematic for statistical tests assuming normality, the Drift Diffusion Model and EZ Diffusion Model assume this type of distribution. Further explanation of the skewness statistical tests are available in the methods section. (a) The positive skew (.98) is statistically significant ($Z = 24.7$) for the word recognition RT's during the oLDT. (b) The positive skew (.83) is also statistically significant ($Z = 15.7$) for the pseudoword RT's from the pLDT.

Fig. 2.

Reading Tendency Index scores were normally distributed and divided into three reading groups derived from tertiles. Readers with no bias for using decoding or word recognition skills to read single words cluster near zero, composing the Balanced Readers (middle tertile). More extreme tendencies are represented further away from zero, Decoders (lower tertile) and Sight Readers (upper tertile).

Fig. 3.

The drift rates for both decoding and word recognition were normally distributed and have been shaded to reflect the members of each reading tendency type. (a) Balanced Readers show generally average to above average rates on both skills. (b) Decoders, including the six subjects qualifying for RD, demonstrate average pseudoword drift rates, but cluster toward the bottom of word recognition drift rates. (c) Sight Readers exhibit average or better word recognition, but also show relatively poorer pseudoword drift rates.

Table 1.

Conceptual framework of cognitive skills influencing single word reading approaches

	Decoders	Balanced Readers	Sight Readers
Decoding skills	Limited	Good	Poorly Developed
Word recognition	Poorly Developed	Good	Limited
Cognitive flexibility	Delayed	Good	Poorly Developed
Verbal Working memory	Limited	Good	Poorly Developed
Visual Working memory	Poorly Developed	Good	Limited
Overall Fluency	Delayed	Good	Limited

Table 2.

Group demographics

	Balanced	Decoders	Sight Readers	Total	Age ($\pm$ SD)	FSIQ ($\pm$ SD)
TDC	9	3	3	15	11.6 (1.6)	114.1 (16.2)
ADHD/-RD	5	5	4	14	12.5 (1.9)	106.0 (16.0)
ADHD/+RD	0	6	5	11	11.9 (1.7)	107.7 (15.6)
Total	14	14	12			
Age ($\pm$ SD)	12.3 (2.1)	11.5 (1.4)	12.1 (1.8)			
FSIQ ($\pm$ SD)	114.4 (18.2)	110.5 (14.6)	103.1 (13.1)			

Table 3.**Symptoms and Reading Scores**

		Balanced	Decoders	Sight Readers	Group effect p-value	Tukey's <i>HSD</i> Post-Hoc
ADHD	Combined/Inattentive Subtype	2/3	8/3	5/3		
Conner's	Cognitive Problems/Inattention	46 (8)	53 (11)	61 (14)	0.004	SR > B, $p = .003$
	Hyperactivity	52 (16)	63 (16)	64 (18)	0.09	
WIAT-III	Word Reading	106 (6)	102 (13)	91 (14)	0.004	B > SR, $p = .004$; D > SR, $p = .027$
	Pseudoword Decoding	107 (8)	101 (16)	93 (20)	0.054	
	Spelling	106 (13)	102 (13)	91 (15)	0.019	B > SR, $p = .015$
D = Decoder, B = Balanced, SR = Sight Reader						
		TDC	ADHD/-RD	ADHD/+RD	Group effect p-value	Tukey's <i>HSD</i> Post-Hoc
ADHD	Combined/Inattentive Subtype		9/5	7/4		
Conner's	Cognitive Problems/Inattention	43 (6)	56 (11)	63 (12)	< .001	AR > T, $p < .001$; A > T, $p = .002$
	Hyperactivity	46 (5)	64 (18)	73 (12)	< .001	AR > T, $p < .001$; A > TR, $p = .001$
WIAT-III	Word Reading	104 (9)	104 (11)	90 (15)	0.007	AR < T, $p = .013$; AR < A, $p = .014$
	Pseudoword Decoding	105 (8)	108 (10)	84 (19)	< .001	AR < T, $p < .001$; AR < A, $p < .001$
	Spelling	106 (10)	106 (12)	86 (14)	< .001	AR < T, $p < .001$; AR < A, $p < .001$

Standard deviations are bracketed; RD = reading disability; Group differences were compared by ANOVA; T = TDC; A = ADHD/-RD; AR = ADHD/+RD;

Table 4.**WIAT-III and Other Reading Characterization Assessments**

Domain	Metric	Balanced	Decoder	Sight Reader	Group <i>p</i> -value	Tukey's HSD <i>post-hoc</i>
Word recognition	High-freq. word drift rate	.29 (.08)	.20 (.05)	.30 (.08)	0.005	B > D, <i>p</i> = .008; SR > D, <i>p</i> = .016
Decoding	Pseudoword drift rate	.21 (.07)	.18 (.06)	.12 (.07)	0.006	B > SR, <i>p</i> = .006; D > SR, <i>p</i> = .049
Verbal Working Memory	Sentence memory (completed items)	18 (2)	18 (3)	15 (3)	0.006	B > SR, <i>p</i> = .007; D > SR, <i>p</i> = .031
Cognitive Flexibility	Intra-/Extra-Dimensional Set Shift					
	Total trials - adjusted	79 (12)	107 (39)	132 (44)	0.003	SR > B, <i>p</i> = .002
	Total Errors	14 (7)	22 (11)	32 (18)	0.006	SR > B, <i>p</i> = .004
D = Decoder, B = Balanced, SR = Sight Reader						
Domain	Metric	TDC	ADHD/-RD	ADHD/+RD	Group <i>p</i> -value	Tukey's HSD <i>post-hoc</i>
Word recognition	High-freq. word drift rate	.27 (.07)	.28 (.09)	.22 (.07)	0.14	-
Decoding	Pseudoword drift rate	.18 (.08)	.19 (.06)	.13 (.07)	0.13	-
Verbal Working Memory	Sentence memory (completed items)	17 (2)	18 (3)	16 (3)	0.45	-
Cognitive Flexibility	Intra-/Extra-Dimensional Set Shift					
	Total trials - adjusted	100 (41)	111 (41)	103 (38)	0.54	-
	Total Errors	23 (20)	25 (12)	19 (11)	0.58	-

Standard deviations are bracketed; Group differences were compared with ANCOVA, where age was covaried.