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Dyslexic and skilled reading dynamics are self-similar

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Abstract The shape of a word pronunciation time distribution supplies information about the dynamic interactions that support reading performance. Speeded word-naming pronunciation and response time distributions were collected from 20 sixth grade Dutch students with dyslexia and 23 age-matched controls. The participants' pronunciation times were modeled and contrasted with a lognormal inverse power-law mixture distribution. Identical contrasts were also conducted on the same participants' response time distributions derived from flanker, color-naming, and arithmetic tasks. Results indicated that children with dyslexia yield slower, broader, and more variable pronunciation time distributions than their age-matched counterparts. This difference approximated a self-similar rescaling between the two group's aggregate pronunciation time distributions. Moreover, children with dyslexia produced similar, but less prominent trends toward slower and more variable performance across the three non-reading tasks. The outcomes support a proportional continuum rather than a localized deficit account of dyslexia. The mixture distribution's success at describing the participants' pronunciation and response time distributions suggests that differences in proportional contingencies among low-level neurophysiological, perceptual, and cognitive processes likely play a prominent role in the etiology of dyslexia.

Keywords Dyslexia · Lognormal · Power-law scaling · Response time distributions · Self-organization of cognitive performance · Speeded word naming

Dyslexia is characterized by non-fluent word recognition and poor spelling performance—all in the absence of sensory impairments, low intelligence, or a lack of educational opportunity (Pennington, 2009, p. 82; Lyon, S. E. Shaywitz, & Shaywitz, 2003; SDN, 2008). Dyslexia is said to be the most prevalent specific learning difficulty. The number of school-aged children estimated to have dyslexia ranges from 6 to 17 %. Definite incidence rates, however, depend on the criteria used to assess the severity of reading difficulty (Fletcher, 2009).

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In the 1970s, scientific and societal recognition of children and adults with severe reading difficulties, who were once believed to be of low intelligence, spawned a long-standing hypothesis of the existence of a group of readers with specific reading problems. Based on a number of epidemiological studies, Rutter and Yule (1975) reported the existence of a distinct group of children who read below the level of their expected intelligence. This group, referred to as children with specific reading retardation, had to be distinguished from a group of children who displayed a general backwardness in reading: A phenomenon usually accounted for by their general lower level of intelligence or educational deprivation.

Rutter and Yule's data revealed a so-called hump in the distribution of reading scores at the low end of the normal curve, suggesting "…that specific reading retardation constitutes more than just the lower end of a continuum" (p. 184). Subsequent, international epidemiological studies have been unable to demonstrate a bimodal distribution in reading scores, indicating that reading difficulties appear to be best portrayed in terms of a continuum (Jorm, Share, MacLean, & Matthews, 1986; Rodgers, 1983; S. E. Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992).

Despite the accepted unimodal distribution of reading scores, the discussion pertaining to qualitatively distinct reading behavior at the extreme lower tail of a reading-score distribution remains. After all, dyslexia (when equated with specific reading retardation) is presently seen as a genetically based neurobiological disorder, caused most likely by a phonological deficit (e.g Lyon et al. 2003; Pennington, McGrath, & Smith, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Alternative causes for the existence of dyslexia are a magnocellular deficit (e.g., Laycock, D.P. Crewther, & Crewther, 2012; McLean, Stuart, Coltheart, & Castles, 2011; Stein & Walsh 1997), a rapid naming deficit (Torppa, Georgio, Salmi, Eklund, & Lyytinen, 2011; van der Ley et al., 2013), and a dysfunctional cerebellum (e.g., Nicolson, Fawcett, & Dean, 2001; Stoodley & Stein, 2013).

Moreover, dyslexic readers tend to score lower than skilled readers on a large variety of cognitive tasks, such as the following: temporal processing, balance and motor control, auditory and tactile processing, mental calculations, among many others (e.g., Elliott & Gibbs, 2008, Hasselman, 2014). Note that these criteria are by themselves neither essential nor specific for the diagnosis of dyslexia (e.g., Blomert & Willems, 2010; Ramus, Pidgeon, & Frith, 2003; Snowling, 2008; Torgesen, Wagner, & Rashotte 1994). We believe that scientists mistakenly view the phenomena that are to some extent related with reading skill as potential causes of the 'disorder'.

The novel approach taken here will help determine if dyslexia should be viewed as a reading impairment that is qualitatively distinct from that of skilled reading and how cognitive activities other than reading may distinguish between dyslexic and skilled readers. As such, we present dyslexic and skilled readers with one reading and three non-reading tasks. Similar non-reading tasks were used previously to distinguish between dyslexic and skilled readers in standard analyses.

This article illustrates how information regarding the underlying dynamics of cognitive activity, such as reading, is revealed by the shape of response time distributions in our studies. Children with and without dyslexia take part in four different cognitive tasks, and their response time distributions are compared. *Response time* is the elapsed time between the presentation of a stimulus and the collection of a participant's response in a laboratory-based cognitive task. It is among the oldest and most widely used measures of cognitive activity (e.g., see Sternberg, 1969). Response time studies are motivated by a simple logic that thought takes time.

Self-similarity in behavior

To understand the approach taken here, we first illustrate how reading can be viewed as a dynamic activity, which sets the stage for the next section in which the so-called cocktail model that underlies our analyses is explained. It is a quantitative modeling technique that offers a new solution to questions about the nature of dyslexia.

The details of our analyses rely on modern, computationally intensive statistical techniques, but a detailed understanding of those procedures is not needed to grasp our essential point. The analysis is rooted in geometry—the *shape* of our participant's response time distributions. Next, the meaning of self-similarity will be elucidated, allowing an answer to the question of whether or not the reading performance of dyslexic readers is qualitatively different from that of skilled readers. The final section of this introduction summarizes our specific research questions and the rationale for using the three additional non-reading cognitive tasks.

Figure 1 illustrates examples of spatial self-similarity. Our fundamental finding, reported below, is that a self-similar rescaling relates dyslexic and age-appropriate reading

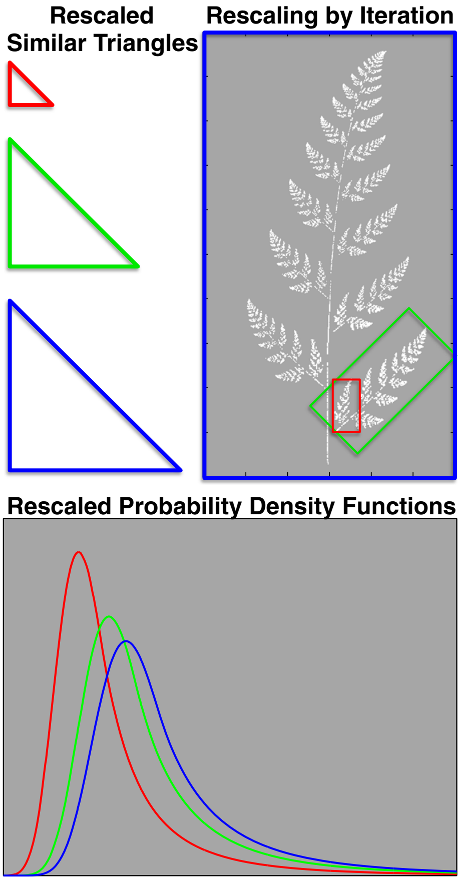

Fig. 1 The figure illustrates three examples of ideal geometric rescaling relations. On the *upper left*, three similar *triangles* are illustrated. They share the same shape, and a proportional rescaling of one yields the others. On the *upper right*, rescaling in a more complex, but recognizable mathematical fern, is illustrated. It was generated by repeatedly reapplying the same mathematical rule—a natural recipe for rescaling. Natural ferns are statistically self-similar; their parts are inexact copies of the whole object. The *lower plot* depicts three probability density functions (i.e., normalized histograms). They too are related by proportional rescaling. Multiplying the taller, leftmost distribution by a positive constant, greater than one, stretches and broadens the resulting distribution, yielding the center distribution. Repeating the operation stretches the distribution further, resulting in the even less peaked rightmost distribution

performances. As we explain, this outcome supports a continuum hypothesis, but goes beyond it in important ways. Rescaling indicates a *proportional* continuum, that is, a ratio-based continuum, in which incremental change is multiplicative rather than the additive change of a linear continuum.

The *implication* of rescaling is that a representative distribution derived from one group, such as participants with dyslexia, may be a self-similar copy of another group's distribution. Thus, the two distributions can be roughly viewed as being generated by qualitatively similar dynamic interdependencies, in which the rescaled group's cognitive dynamics unfold on a slower, *dilated* time scale. Outcomes such as this offer a principled basis for a proportional continuum account of dyslexia. It provides a formal basis for relating the two categories of performance, self-similarity or proportional rescaling.

Of course, rescaling is a mathematical relationship. Assuming appropriate renormalization, distribution functions other than our cocktail distribution can be rescaled. The crucial outcome described in our "General discussion" section is the observation that ostensibly different categories of human behavior—skilled and unskilled reading—are related by rescaling. Our next section overviews the scientific motivation for the description of response time distributions we adopted as a model for our participants' reading and other cognitive performances.

Reading as a dynamic activity

Pronouncing a visually presented word feels easy for most skilled readers. However, successfully *articulating* just one phoneme requires speakers to maintain a complicated spatiotemporal arrangement among 70 or more muscles (Kelso, Saltzman, & Tuller, 1986; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Turvey, 1990; 2007). Coordinative synergies facilitate this apparently unwieldy activity. Coordinative synergies are reciprocal couplings among relevant component processes—couplings that reduce the variety of possible arrangements among the bodily processes governing speech and many other acts (Tuller, Turvey, & Fitch, 1982; Turvey, 1990; 2007).

Synergetic links simplify action by imposing relationships among articulation processes. They act as constraints, compressing the potential range of possible utterances. The relationships among ones limbs that are maintained while walking illustrate a coordinative synergy. To keep from stumbling, both legs must maintain precise coordinative relationships. For instance, actually putting "both feet forward" while walking results in a fall. In fact, the required delicate timing and balance among our leg movements is revealed in occasional missteps while walking. A slight but unseen change in the relation between the floor and our feet can easily cause a fall. Our legs are not rigidly tethered, but are nonetheless mutually constrained by a host of functional and biomechanical demands.

Cognitive and perceptual dynamics entail similar synergies, but they unfold on faster timescales than movement and articulatory dynamics. Cognitive synergies rely more heavily on patterns of neurophysiological coordination (e.g., see Buzáki, 2006). For example, skilled readers comfortably *recognize* many printed words in less than 200 ms, but often require more than twice as much time to accurately *pronounce* presented items (Strijkers & Costa, 2011).

Modeling response time distributions using the cocktail model

In the present studies, we will model children's response time distributions after a recent and successful description of skilled adult readers' pronunciation time distributions (Holden & Rajaraman, 2012). The model, is called the "cocktail" model because it describes empirical response time distributions in terms of probabilistic mixtures of samples from either a lognormal or an inverse power-law distribution.

Both lognormal and inverse power-law probability distributions are symptomatic of discretely sampled synergetic dynamics (see Holden & Rajaraman, 2012). A *lognormal distribution* is a positively skewed distribution that appears as a symmetric Gaussian distribution after a logarithmic transform of the measured variable (Evans, Hastings, & Peacock, 2000; Limpert, Stahel, & Abbt, 2001). Lognormal distributions are common in chemical and biological systems; they emerge in the presence of multiplicative or proportional operators. Lognormal distributions indicate proportional amplification that is subject to random sources of perturbation. Thus, exchanges among processes supporting the outcome are proportionally intertwined, and these contingencies give rise to the positive skew that is characteristic of a lognormal distribution. This is in stark contrast to *additively* combined stochastic variables that yield a standard Gaussian distribution.

An *inverse power-law* distribution, on the other hand, expresses a more pronounced positive skew than a lognormal distribution (Clauset, Shalizi, & Newman, 2009). When the skewed heavy tail of a response time distribution decays as a power function, the probability of observing a given response time, $p(RT)$, is proportional to the inverse of response time, raised by a scaling exponent α, $p(RT) \approx RT^{-\alpha}$. Power-law behavior is symptomatic of circular feedback dynamics, such as those used to generate the mathematical fern depicted in Fig. 1, revealing self-similar patterns.

The cocktail model leverages recent results from the science of complex systems that specifies correspondences between the interactions among a system's governing processes and the shape of the system's output distribution (van Rooij, Nash, Rajaraman, & Holden, 2013; West & Deering, 1995). Crucially, the characteristic dynamics among the cognitive processes can be explored without identifying the sub-functions or structural architecture of the system (Holden, Van Orden, & Turvey, 2009). For the present studies, the most important point is that if only the location parameters of the cocktail distribution change as a function of two experimentally contrasted distributions, then the two distributions are related by an elementary self-similar rescaling.

The current studies

Dyslexic and skilled readers are presented with four tasks, namely, a flanker task, speeded word-naming, color-naming, and a simple arithmetic task. Each task contains 560 stimuli to which the participant has to respond by either a vocal or a manual response (see for details the "Method" section). For each task, the cocktail model is fit to each participant's response time distribution. The resulting model parameters are then used to contrast the performances as a function of both tasks and the participants' reading status. The goal is to garner information about the cognitive, perceptual, and motor dynamics that undergird the performance of individuals with dyslexia as compared with those of age-matched controls.

Our selected laboratory tasks impose perceptual and cognitive demands that are differentially related to reading itself. This allows an assessment of the degree to which dyslexia is functionally localized to reading itself. For example, the *flanker task* is thought to emphasize response inhibition, a more general perceptual-motor skill than reading. Of course, the *speeded word naming* emphasizes reading. The *color-naming* task indexes a participant's ability to identify and pronounce visually presented stimuli without imposing an explicit reading requirement. Finally, the *arithmetic task* is used to examine performance on a high-level cognitive activity that imposes simpler symbol recognition requirements than reading. Each task entails different explicit goals, but all tasks likely rely on a shared set of more general lower-level perceptual and cognitive activities, such as perceptual and visual encoding, discrimination, and motor control.

Our two primary research questions are the following: First, is dyslexia a qualitatively distinct and perhaps structural deficit, or is it symptomatic of a continuum of impairment in reading skill? Naturally, a clear answer to this question has implications for the nature and scope of interventions. In fact, rescaling behavior points to a *proportional* continuum rather than the standard additive continuum associated with a Gaussian distribution of reading scores. Second, do dyslexic readers' performances differ only in speeded word naming, or do they also differ on tasks that do not explicitly require reading.

Method

Participants Twenty dyslexic children (13 boys, 7 girls) and 23 non-dyslexic children (8 boys, 15 girls) were recruited from the sixth grade of Dutch primary schools. Participants ranged in age from 11 to 13 (*M* age=12.3 years). The dyslexic children all had an official diagnosis of dyslexia provided by an educational or child psychologist. All participants completed two widely used reading tests: the standardized word reading "One-Minute Test" by Brus and Voeten (1973) and a standardized pseudoword reading test "Klepel" (van den Bos, lutje Spelberg, Scheepstra, & de Vries, 1994). Our goal was to verify that the recruited dyslexic children's reading skills were substantially below normal and that non-dyslexic children maintained average or above average reading skills. We used scaled scores on the One-Minute Test and Klepel, with a mean of 10 and a standard deviation of three, as our selection criteria. Our criteria were as follows: scores of 6 or lower for the dyslexic children and standard scores of 12 or higher for the non-dyslexic children. Informed consent was obtained via a passive parental consent procedure.

Materials and procedure Participants completing the *flanker task* were required to decide, as quickly and accurately as possible, whether the target arrow that was displayed in the middle of a row of arrows on a computer screen pointed to the left or the right. Participants responded by pressing the corresponding button on a button box as fast as possible. The left and right response buttons were labeled with a copy of the left and right facing target arrows (e.g., ← and →). Response times and accuracy were recorded. The flanker task presented 560 trials, and in each trial, a row of five arrows was displayed on the screen. All arrows could be facing in the same direction (congruent trials, e.g., → → → → →), or the outer four arrows (distracters) could face in a different direction than the middle arrow (incongruent trials, e.g., ← ← → ← ←). Additionally, neutral trials were added in which the middle arrow was not surrounded by four other arrows, but by four dashes instead (e.g., - - → - -). The trials were presented in a random order.

The speeded word-naming task The naming target items consisted of 560 Dutch single-syllable words with a frequency per million >0, selected from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). We generated three different presentation orders of the word-naming items by randomizing the word list three separate times. Participants were randomly assigned to name the items in one of the three orders.

Participants were instructed to pronounce each word into a microphone as quickly and accurately as possible. Before the task started, participants completed 15 practice trials to become familiar with the procedure. In each trial, the participant was presented with one of the 560 target words, preceded by a fixation signal (+ + +), visible for 173 ms. After this fixation signal, a blank screen was visible for 200 ms, after which the target word appeared on the screen. The inter-trial interval was 607 ms. All stimuli appeared in the center of a laptop screen and remained on the screen for 10 s when no response was recorded. The words were presented in a sequential order to make it possible to manually record wrong answers and erroneous reaction times (for example, when the voice key recorded a sound before the stimulus word was read).

The color-naming task On each trial, participants named the color of a presented color patch as quickly and accurately as possible. The task presented 560 trials, each consisting of one randomly selected colored square at the center of a computer screen. The square, measuring 100 × 100 pixels, could be one of five colors as follows: red, yellow, blue, purple, or black. The order of the colors was randomized. Again, a voice key recorded the onset of the pronunciation as an indication of the participant's response time. All color-naming errors were recorded manually by the experimenter.

The arithmetic task In the arithmetic task, each of 560 trials consisted of an addition sum together with an answer that was either correct (e.g., $3+6=9$) or incorrect (e.g., $4+3=2$). Answers to the sums were always below 10. Participants decided, as quickly and accurately as possible, whether the presented sum was correct or not. They had to respond by pressing the corresponding button on a button box. A red and a green sticker were placed just above the buttons to aid the memory of which button belonged to which answer. The sums were presented in a random order. Both the response times and whether the responses were correct or incorrect were automatically recorded.

Statistical analyses Our primary focus was contrasts among the patterns of variability expressed by the participant's pronunciation and response time distributions. First, we used a nonparametric Gaussian kernel density estimator to generate smoothed probability density functions for each participant's empirical distribution (e.g., see Silverman, 1989). Following that, we applied parametric maximum likelihood distribution fitting techniques to approximate the empirical distributions with the idealized cocktail distribution (Van Zandt, 2000). The fitting routine returns four "free" and three determined cocktail model parameters. We analyzed and reported only the five parameters that fully determine the shape of the cocktail density function: the mode and variance of the lognormal portion (Ω_{LN}, σ_{LN}), the power-law scaling exponent (α) and the proportion of power law in the tail of the mixture (ρ_{PL}), and the power-law mode (Ω_{PL}, see Holden and Rajaraman (2012) for more details).

As mentioned before, the cocktail model successfully approximated a large database of skilled *adult* response time distributions of word pronunciation in the speeding naming paradigm (Holden & Rajaraman, 2012). Overall, children, especially children with dyslexia, tend to be less skilled readers than adults. One practical implication is that children's empirical pronunciation time distributions tend to be more idiosyncratic than adults; they are more likely to contain false starts and empty gaps. The children's datasets are less concentrated across the typically measured time intervals. This imposed some limitations on our ability to successfully model the empirical distributions. Idealized distribution functions assume homogeneous variability. As a consequence, we sometimes had to adapt common statistical goals and practices to overcome the inherent noisiness of the children's pronunciation and response time distributions. We included error responses in the flanker and arithmetic fits. The flanker error rates were similar across groups and low (4 %), including them yielded minor fit changes. Both group's arithmetic performance was similar, but more error prone (9 %). Including errors, again, revealed little change in fits. We did exclude word- and color-naming errors from our fits. The naming error rates differed by group (control, 4 % dyslexic, 11 %), and both tasks coded invalid voice responses as errors.

Notably, in the analysis of each task, we eliminated participants with distributions that returned values of any of the five key cocktail parameters greater than the 95th percentile of the overall distribution for that task. Selectively eliminating participant's data from analyses due to poor fits introduces an opportunity for selection bias that risks making our groups appear more similar quantitatively. As such, we computed a *Z*-test for equal proportions to evaluate this possibility in each task. A *non-significant* outcome of this test indicates that our selection criteria likely *did not* differentially eliminate participants from the two reading status conditions. None of the individual *Z*-tests reliably distinguished the original sample proportions from the proportions that passed the statistical selection criteria. We found no other indications that our selection criteria fundamentally distorted or misrepresented the between-group differences we describe.

Results

All pronunciation and response times less than 300 ms or greater than 6 s, or word and color naming trials that resulted in an error, were eliminated from our statistical analyses. Beyond that, we imposed two global criteria to claim a statistically reasonable fit. The *p* value returned by a bootstrapped Kolomgrov-Smirnov (K-S) test for discrepancies between the ideal distribution and the empirical distribution had to be 0.1 or larger, *and* all the parameter values returned by the maximum likelihood estimation routine had to fall within ranges that plausibly specified unimodal lognormal and power-law mixture density functions. The value of the power-law scaling exponent and the power-law onset threshold were the most useful indices in this regard. Scaling exponents in excess of ~10 tend to indicate that the power-law portion of the mixture is superfluous. Similarly, bimodality or an unnecessary power-law portion is indicated if the fitting routine returns a power-law threshold that is widely separated from the lognormal portion of the distribution. All standard errors used in our statistical contrasts were generated with the standard jackknife procedure (Efron & Tibshirani, 1993). Jackknifed standard errors are derived from the empirical distribution rather than by classical parametric assumptions.

Given both the aforementioned *p* value and parametric range constraints, and collapsing across the participant's reading status factor for now, the cocktail model successfully approximated 81, 79, 81, and 67 % of the flanker, pronunciation time, color-naming, and arithmetic distributions, respectively. The arithmetic response time distributions were much slower and far more variable than those of the other three tasks, M_{Arith}=1,472 ms, (SD=1,071 ms), M_{Others}=678 ms, (SD=358 ms). Since the distributions derived from each task were comprised of no more than 560 observations, the increased spread likely explains the smaller portion of successful arithmetic distribution fits.

We now begin our discussion of the outcomes of the between-group performance contrasts for the flanker task, then speeded word-naming, color-naming, and finally the arithmetic task. This task sequence approximates a continuum beginning with the fastest, least variable task and ending with the slowest and most variable task. We fit each response time distribution with the cocktail model and sorted the resulting parameters within the two reading groups according to the value of the power-law scaling exponent (α). The scaling exponent serves as an index of the relative skew of the distributions. Roughly, smaller α values indicate greater skew.

Flanker task Data from a total of 20 participants with dyslexia and 23 controls were available for the flanker contrasts. A total of 35 participants' distributions passed the selection criteria, 16 with dyslexia and 19 controls. The resulting dyslexic-control proportion of 46 % *did not* reliably differ from the originally sampled proportion of 47 %, $Z=-0.09$, $p>0.05$. The (modified) flanker task is thought to measure response inhibition as participants distinguish congruent and incongruent arrow orientations (Eriksen & Eriksen, 1974). For both reading groups, the flanker task elicited the fastest responses—closest to the lower censoring boundary of 300 ms used for all tasks.

Figure 2 depicts three representative control and dyslexic flanker distributions. The two left plots were selected from above the third quartile of the α ranks, the middle two plots were selected from the median of the α distribution, and the two right plots were selected from below the first quartile. In the case of the dyslexic flanker response times, the smaller of the two α values around the median was selected since the number of participants of that group was evenly divisible by 2.

The two reading-skill groups distributions' expressed only slight shape differences. The lognormal standard deviation, σ_{LN} is reliably larger for participants with dyslexia M_d=0.20 (SD=0.04) than for controls M_c=0.17 (SD=0.02), by an independent sample t test, $t(33)=2.11$, $p<0.05$. Contrasts between participants with dyslexia and controls for the other cocktail variables failed to reveal reliable differences. So, from the perspective of the cocktail description of the distributions, the group with dyslexia's fastest flanker trials was typically more variable than controls. A visual contrast of the model distributions in the center column of Fig. 2 illustrates this difference; the control participant's density function is approximated by a narrower cocktail distribution, and the model distribution's mode peaks at a larger density value than the model distribution characterizing its counterpart distribution for a child with dyslexia, directly below it.

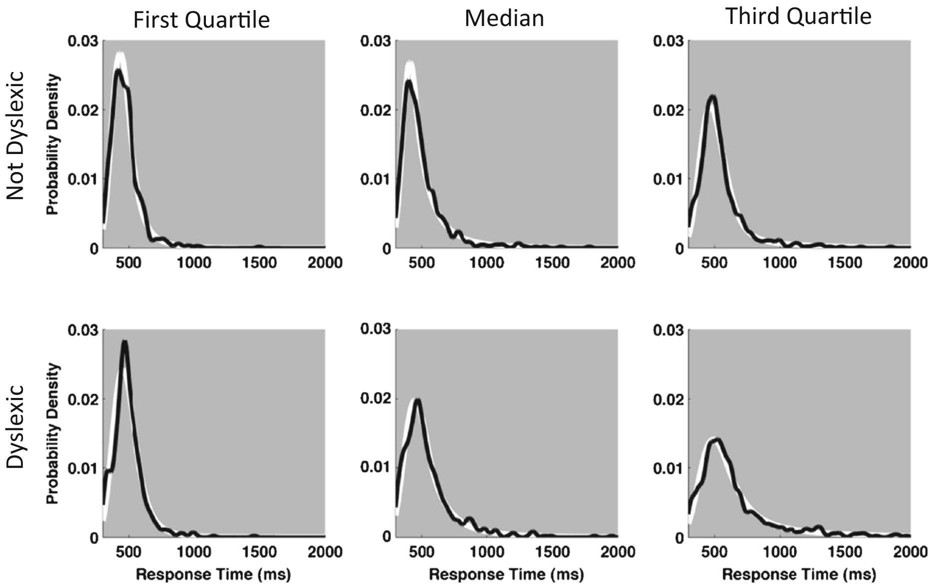

Fig. 2 Three representative control (*top row*) and dyslexic (*bottom row*) flanker distributions. The empirical distributions are depicted in *black*, the corresponding cocktail model descriptions in *white*. The distributions are ordered by their α values from high to low, tracking an increasing relative skew in the distributions, from left to right. The *left-hand plots* were selected from above the third quartile of the respective group's distribution of α values (*top*, α=6.23; bottom, α=6.39). The two *center plots* are representative of median α values (*top*, α=4.56; *bottom,* α=4.52), and the two *right-hand plots* were selected from below the first quartiles of their α respective distributions (*top*, α=3.04; *bottom*, α=2.93). The flanker task distributions are nearest to the omnibus censoring value of 300 ms. This explains why the very front-end of the distributions sometimes appear truncated in the plots

Speeded naming task Data from 20 participants with dyslexia and 23 controls were available for the speeded naming contrasts. A total of 34 participants' data passed the selection criteria, 16 with dyslexia, and 18 controls. The resulting dyslexic-control proportion of 47 % *did not* differ reliably from the originally available proportion of 47 %, $Z \approx 0$, $p > 0.05$. Figure 3 depicts three representative control and dyslexia pronunciation time distributions. We presented the larger of the two α values around the median due to the even N size in each group. In this case, the differences between the two groups were reliably expressed across three separate parameters. The dyslexia group's lognormal location parameters were reliably larger than controls, $t(32)=5.33$, $p<0.05$, Ω_{LN} $M_{\mathrm{d}}=6.43$ (SD=0.09) versus Ω_{LN} $M_{\mathrm{c}}=6.27$ (SD=0.09). Likewise, the dyslexia group's power-law location parameters were reliably larger than controls, $t(32)=4.41$, $p<0.05$, Ω_{PL} $M_{\mathrm{c}}=580$ (SD=54) versus Ω_{PL} $M_{\mathrm{d}}=688$ (SD=84). In addition, on average, a larger proportion of samples from the power-law distribution was required to approximate the pronunciation time distributions for individuals with dyslexia, relative to controls, $t(32)=3.04$, $p<0.05$, ρ_{PL} $M_{\mathrm{d}}=0.25$ (SD=0.11) versus ρ_{PL} $M_{\mathrm{c}}=0.14$ (SD=0.11).

The fact that the bulk of the distinction between the two groups' pronunciation time distributions is captured by differences in the cocktail distribution's location parameters is of particular interest. If just the location parameters of the cocktail distribution change as a function of a contrast, then the two aggregate distributions indicated by the averaged parameters are related by an elementary self-similar and proportional rescaling—the same relationship depicted in Fig. 1. Rescaling means that the distribution resulting from averaging across participants with dyslexia is a self-similar copy of the control participants' averaged distribution. In this case, the rescaling is not exact, but it is very nearly so. Both distributions can be

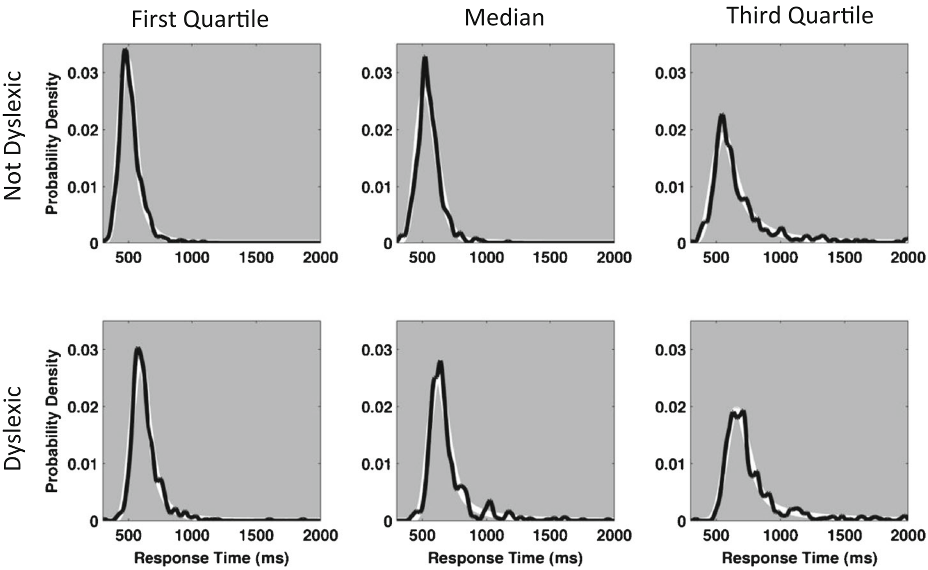

Fig. 3 Three representative control (*top row*) and dyslexic (*bottom row*) pronunciation time distributions. As before, the empirical distributions are depicted in *black*, and the corresponding cocktail fit is *white*. The example distributions are ordered by their alpha values from large to small. As such, the relative skew of the distributions tends to increase from left to right. The *left-hand plots* were selected from those greater than the third quartile of the respective group's alpha (α) distribution (*top*, $\alpha=8.62$; *bottom*, $\alpha=7.03$). The two *center plots* are representative of median α values (*top*, $\alpha=5.40$; *bottom*, $\alpha=4.72$), and the two *right-hand plots* were selected from those falling below the first quartiles of their respective α distributions (*top*, $\alpha=4.38$; *bottom*, $\alpha=3.60$)

roughly viewed as being generated by qualitatively similar dynamic interdependencies, in which the dyslexic's reading dynamics simply unfold on a slower or dilated time scale. Outcomes such as this offer a principled basis for a *proportional* continuum-based account of dyslexia. Beyond that, they provide a basis for relating the two categories of performance: self-similarity. We revisit this issue in the "General discussion" section. Next, we contrast the reading groups' performance in a color-naming paradigm. As with the flanker task, the goal is to determine if between-group differences in performance emerge in tasks that do not emphasize reading skill.

Color-naming task Data from a total of 43 participants were available for the color-naming contrasts, 20 with dyslexia and 23 controls. A total of 15 with dyslexia and 19 controls passed the selection criteria. The resulting dyslexic-control proportion of 43 % *did not* differ from the originally available proportion of 47 %, $Z=-0.43$, $p>0.05$. Figure 4 depicts three representative control and dyslexic color-naming distributions. The smaller of the two α values around the median was chosen for the controls. Overall, the participants with dyslexia produced reliably broader and more skewed distributions, as we now explain.

The participants with dyslexia expressed *less* variable lognormal standard deviations, $t(32)=-2.31$, $p<0.05$, M_d $\sigma_\mathrm{LN}=0.19$ (SD=0.03) versus M_c $\sigma_\mathrm{LN}=0.22$ (SD=0.04). This indicates that, on average, the fastest color-naming responses for the participants with dyslexia were slightly more similar than those of the control group. Notably, this effect points in the opposite expected direction of our working hypothesis that anticipates control's performance to be

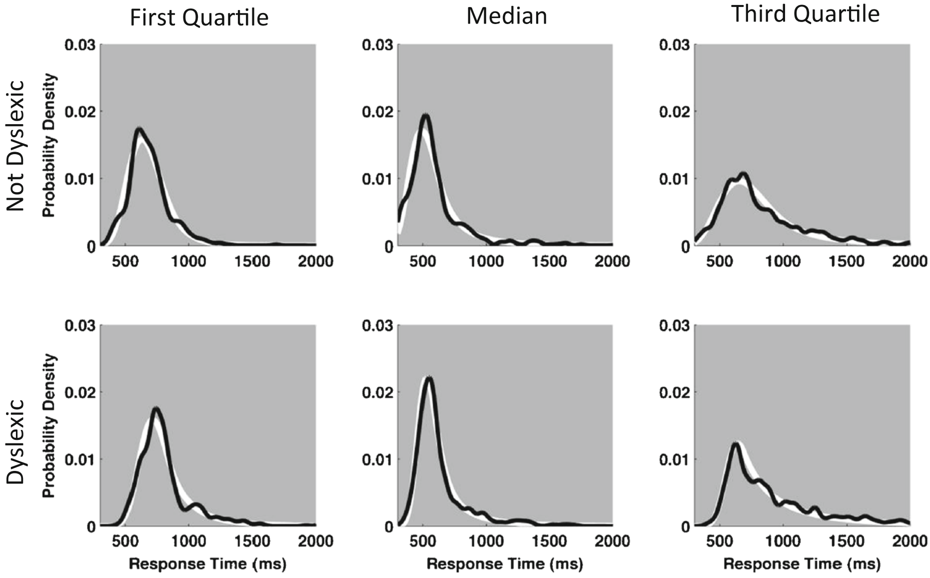

Fig. 4 Three representative control (*top row*) and dyslexic (*bottom row*) color-naming distributions. As in the previous task figures, empirical distributions are depicted as *black lines*, and the corresponding cocktail fits are plotted as *white lines*. The distributions are ordered by their α values from high to low, resulting in the relative skew of the distributions to increase from left to right. The *left-hand plots* were selected from those participants with alphas greater than the third quartile of their respective group distribution of α values (*top*, $\alpha=7.29$; *bottom*, $\alpha=5.63$). The two *center plots* are representative of the median α value (*top*, $\alpha=4.76$; *bottom*, $\alpha=4.34$), and the two *right-hand plots* were from the selected distribution of participants with alpha values that fell below the first quartiles of their α respective distributions (*top*, $\alpha=3.97$; *bottom*, $\alpha=3.09$)

generally more stable and accurate than that of individuals with dyslexia. It is, however, a very modest difference, amounting to only an 11-ms difference in linear units of response-time standard deviation. By contrast, the participants with dyslexia expressed a reliably smaller power-law scaling exponent, α, than controls $t(32)=2.41, p<0.05$, $\alpha\ M_d=4.39$ (SD=0.72) versus $\alpha\ M_c=5.13$ (SD=1.11). In addition, participants with dyslexia expressed a relatively larger proportion of power-law samples in the tail of their distributions than controls, $t(32)=4.10$, $p<0.05$, $\rho_{\mathrm{PL}}\ M_{\mathrm{c}}=0.25$ (SD=0.11) and $\rho_{\mathrm{PL}}\ M_{\mathrm{d}}=0.39$ (SD=0.10). Overall, the pattern of differences amounts to increased variability for participants with dyslexia, relative to controls.

Both controls and participants with dyslexia yielded slower and more variable color-naming distributions than their respective flanker or word-naming distributions. Moreover, there were between-group differences within the color-naming task. The participants with dyslexia's response time distributions were more variable overall. This outcome is notable because one expects color naming to pose few, if any, reading-related demands, relative to word naming, for instance. Nevertheless, the two groups' color-naming performances are statistically distinguishable. The extant literature reports similar outcomes: slowed color naming, picture naming, digit naming, and even slowed articulatory gestures in contrasts of dyslexic and age-matched controls (Fawcett & Nicolson, 2002; Nicolson & Fawcett, 1994a). Together, these results are consistent with a continuum hypothesis of dyslexia as we will discuss in more detail in the General discussion section. First, we describe the outcomes of the reading group contrast in the context of arithmetic performance.

Arithmetic task Of the 43 initially available participants, 29 participant's arithmetic data passed the selection criteria, 11 with dyslexia, and 18 controls. The resulting dyslexic-control proportion of 38 % *did not* reliably differ from the originally available proportion of 47 %, $Z=-0.93, p>0.05$. Figure 5 depicts three representative control and dyslexic arithmetic distributions (again ordered by α values; for the controls, the larger of the two α values around the median is depicted). Both categories of participants yielded distributions that were slower and more broadly skewed than those arising from the flanker or the word- and color-naming tasks. Thus, we increased the maximum limit on the *x*-axis of Fig. 5 to accommodate these more variable and skewed distributions.

The arithmetic task yielded, by far, the broadest distributions for both the groups of participants. Nevertheless, the cocktail description plausibly captured the majority of the empirical distributions. The power-law scaling exponent α was reliably smaller for readers with dyslexia $M_d=3.77$ (SD=0.56) than for controls $M_c=4.52$ (*SD*=0.94), $t(27)=-2.67$, $p<0.05$. The remaining parameters did not yield a significant difference between the dyslexic children and their controls.

Representative omnibus distributions Averaging the four free and fifth determined cocktail parameters as a function of reading group yielded two sets of composite parameters that each serve as stand-ins for their respective group's performance. The mode of the lognormal front-end of the aggregated cocktail density function for participants with dyslexia is the average of all the individual dyslexia Ω_{LN}'s and so on for σ_{LN}, α, Ω_{PL}, and ρ_{PL}. The averaged parameters were used to generate an omnibus (composite) distribution that is representative of the entire group. Figure 6 depicts the contrast of the two omnibus distributions for word naming in dark gray. As expected, the omnibus distribution of the participants with dyslexia is broader and expresses more skew than that of the age-typical controls. Furthermore, for both groups, the omnibus word-naming distributions are most closely related to the aggregated flanker distributions (Fig. 6, in black). Both the omnibus flanker and word-naming distributions differ in

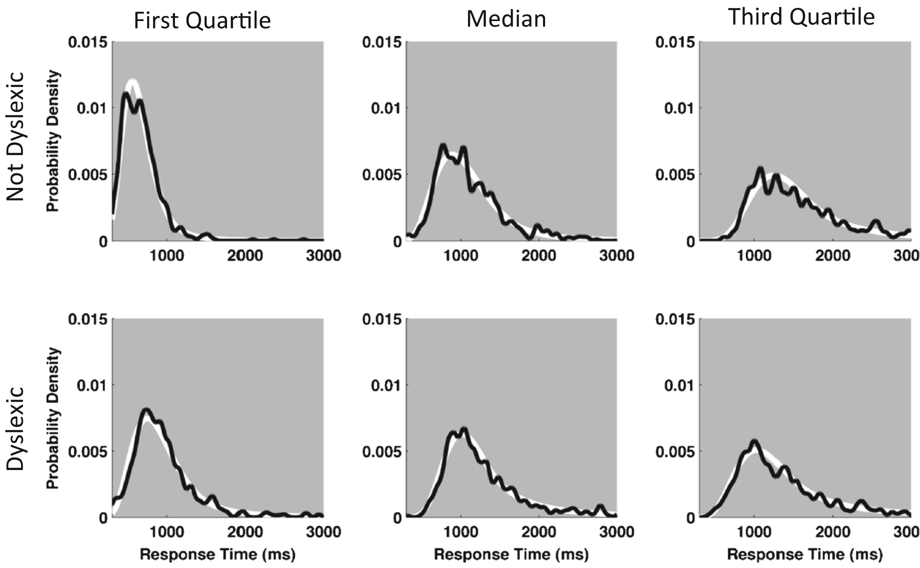

Fig. 5 Three representative example control (*top row*) and dyslexic (*bottom row*) arithmetic distributions. The empirical distributions are depicted as *black lines*, the corresponding cocktail fits as *white lines*. The distributions are ordered by their α values from large to small, thus indicating the relative skew of the distributions as increasing from left to right. The *left-hand plots* were selected from those participants with α greater than the third quartile of the respective group's distribution (*top*, α=5.70; *bottom*, α=4.69). The two *center plots* are representative of the median α values (*top*, α=4.58; *bottom*, α=3.62), and the two *right-hand plots* are representative of those below the first quartiles of their respective alpha (α) distributions (*top*, α=3.46; *bottom*, α=3.08). Note that the range of the *x*-axis extends to 3,000 ms instead of 2,000 ms to accommodate the heavier tails of the arithmetic distributions

shape from the color-naming (Fig. 6, in light gray) and arithmetic distributions (Fig. 6, in white), which are more skewed and variable (an overview of all averaged cocktail parameters appears in Table 1).

Depicting the reading-group performances as related distributions naturally evokes a proportional continuum hypothesis. The performance of both groups was modeled by the same distribution function; they differed primarily in their parameter values. Moreover, the within-task differences between the reading groups, specifically in the case of the speeded naming task, resembled a self-similar rescaling. This implies that the primary difference between participants with dyslexia and controls can be described in terms of differences in the relative coherence among the cognitive and neurophysiological dynamics that support reading activities (cf. Goswami, 2011).

Figure 7 displays the same aggregated distributions depicted in Fig. 6 but as contrasts between participants with dyslexia (white line) and the age controls (black line). For each of the four tasks, the omnibus distributions aggregated over the participants with dyslexia express slightly more skew and are broader than those of the controls. While the between-group differences for the tasks other than reading are subtle, this effect is nevertheless apparent in each task. One might choose to view any given subset of these differences as potentially unreliable. Nevertheless, the performance of children with dyslexia never outpaced their peers on any of the other presented tasks.

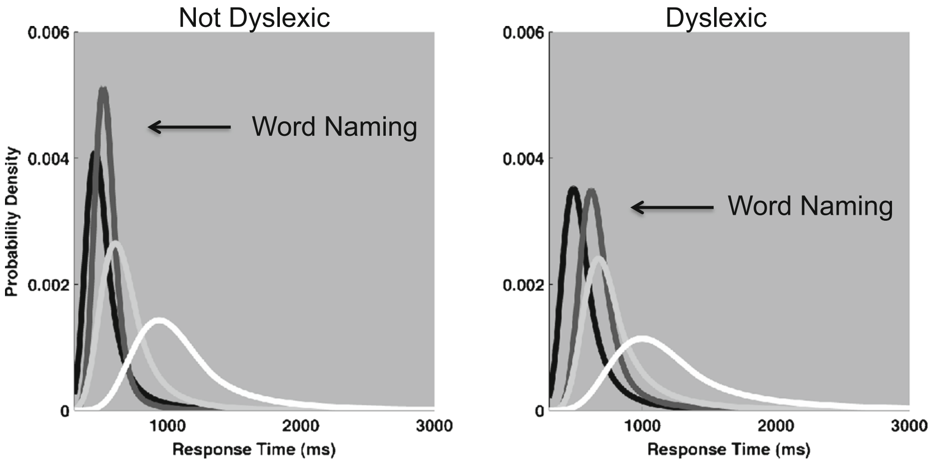

Fig. 6 The *left-hand plot* depicts the representative reading control group distributions for each of the four tasks. The *right-hand plot* depicts the four representative task distributions for the participants with dyslexia. Each distribution was generated using jackknifed averages of the four free cocktail parameters within each group as a function of task. The range of the *x*-axis now extends to 3,000 ms to allow the depiction of the two arithmetic distributions. The two groups track a qualitatively similar performance profile, but the group with dyslexia yielded broader, more variable aggregate performances in each task. The largest between-group discrepancy in the distribution shapes appeared in the speeded naming task

This outcome can be understood as representative of a broader and more general pattern in the established dyslexia literature: Dyslexics display a range of subtly decremented performances in tasks that probe skills other than those probed by direct reading-skill assessments (Fawcett & Nicolson, 1994; Nicolson, & Fawcett, 1994b; Pennington 2009). Our general discussion focuses on how this pattern can be situated by the multiplicative and interdependent coordinative dynamics thought to give rise to the patterns of variability described by the cocktail model.

Table 1 Averaged cocktail parameters for each reading group across the four tasks

Reading Group										
	Control					Dyslexia				
Task	Ω_{LN}	σ_{LN}	α	Ω_{PL}	ρ_{PL}	Ω_{LN}	σ_{LN}	α	Ω_{PL}	ρ_{PL}
Flanker	6.15	0.17	4.76	533	0.31	6.19	0.20	4.89	569	0.29
Word naming	6.27	0.14	5.69	580	0.14	6.43	0.16	4.76	688	0.25
Color naming	6.45	0.22	5.13	774	0.25	6.53	0.19	4.39	781	0.39
Arithmetic	6.87	0.24	4.52	1,254	0.30	6.99	0.29	3.77	1,388	0.33

The averaged cocktail parameters used to generate the representative aggregate distributions appearing in Figure 6, as well as the power-law threshold (Ω_{PL}). Together, the parameters index the shape of each reading group's distributions for the flanker, word-naming, color-naming, and arithmetic tasks. By convention, the Ω_{LN} and σ_{LN} presented are in base *e* logarithmic units. The parameters are ordered according to the values of Ω_{LN}. Both groups track the same approximate pattern for σ_{LN} and Ω_{PL}, as a function of task. By contrast, the parameters that index the evolution of the power-law portion in the tail of the mixture (ρ_{PL} and α) display a less systematic pattern of influence. Note, the averaged parameters were subject equations of constraint A7 and A8, described in Appendix A of Holden and Rajaraman (2012) to insure smooth and continuous density functions

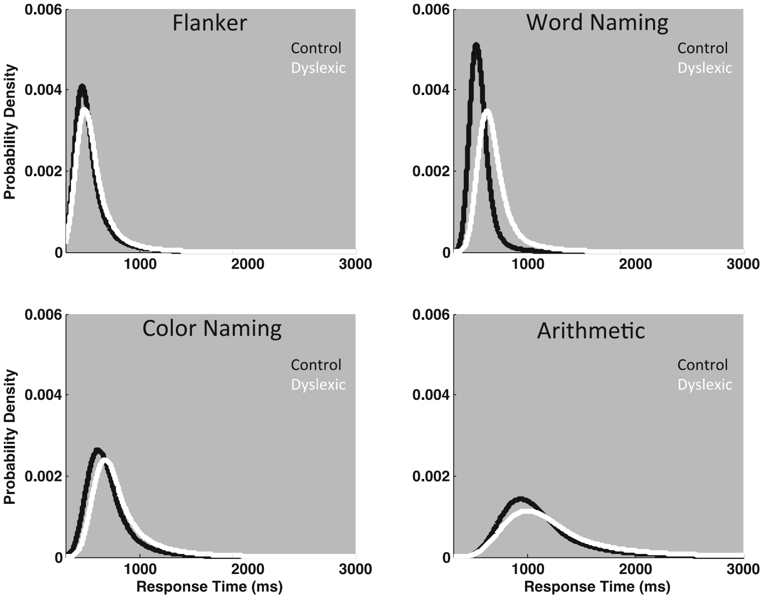

Fig. 7 Task by task contrasts between the control participants and participants with dyslexia for each of the four tasks. Ideal distributions that are representative of the control participants are depicted as *black lines*. Ideal distributions representative of participants with dyslexia are depicted as *solid white lines*. The *upper left plot* depicts the flanker task, the *upper right plot* depicts speeded naming. The *lower left plot* depicts the color-naming distributions, and the *bottom right plot* depicts the arithmetic distributions. The participants with dyslexia consistently reveal slightly slower and/or more variable performance profiles

General discussion

Overall, participants classified as dyslexic produced combinations of slightly slower, more variable or skewed omnibus distributions than the age-typical reading controls in both the word-naming and the remaining non-reading tasks. While there was overlap in the shapes of the individual distributions, this basic pattern held statistically at the level of individual and group distributions. For both reading status groups, flanker performance was the fastest and most stable. Flanker performance also revealed the faintest quantitative discrepancy between the two groups. As expected, the speeded naming distributions revealed more dramatic differences between the two groups. However, the color-naming and arithmetic tasks also distinguished the two aggregate reading-skill distributions.

Reading aloud is a widely practiced skill in school and children's everyday lives. By contrast, the activities demanded of our participants in the flanker, color-naming, and arithmetic tasks required relatively novel instantiations of typical recognition and arithmetic activities. For instance, some involved arbitrary mappings between presented stimuli and collected responses (e.g., yes=right-hand button, no=left-hand button). Compared to reading aloud, the arithmetic task is perhaps the least practiced and likely required considerable cognitive effort from the participants. Thus, one plausible interpretation of our collection of experimental outcomes is that the age-appropriate readers are expressing a learned and practiced skill and that the participants classified as dyslexic have made less progress developing that skill over their life span. It is not a simple *absence* of the skill, but a notable *weakness* of skill in comparisons with peers.

If reading skill arises from more general perceptual, neurophysiological, and biological processes, then dyslexia may well be a problem of assembly and coordination—enacting synergies among processes—rather than a simple absence or impairment of a dedicated reading process. Wijnants, Hasselman, Cox, Bosman, and Van Orden (2012) used time series techniques to examine coordination in a dyslexic's performance across successive naming trials. Between-trial variability indicated reductions in the relative stability of the faster time scale of within-trial coordination activity (e.g., see Holden et al., 2009). Wijnants et al. also concluded that dyslexia entails dynamical instabilities in the coordination among components necessary to read. This outcome corroborates the present finding of more variable distributions and may explain why dyslexic readers reveal impairments in so many distinct tasks (Bosman, van Leerdam, & de Gelder, 2000; Bosman, Vonk, & van Zwam, 2006; Bowers & Wolf, 1993; Fawcett, & Nicolson, 2002; Vaessen, Gerretsen, & Blomert, 2009) and modalities (Buchholz & Davies, 2005; Facoetti & Molteni, 2001; Jones, Branigan, & Kelly, 2008; Livingstone, Rosen, Drislane, & Galaburda, 1991; Marinella, Angelelli, Di Filippo, & Zoccolotti, 2011; Stein & Walsh 1997) as well as motor, cognitive, and linguistic processes (Nicolson & Fawcett, 1994a, b; Ramus et al., 2003; Savage, 2004; Stoodley, Fawcett, Nicolson, & Stein, 2005; Torgesen et al., 1994; Valdois, Bosse, & Tainturier, 2004).

Implications of self-similar rescaling

To understand dyslexia, scientists must bridge the gap between typical and compromised reading performance. Traditional statistics, such as an average response or reading time, portray dyslexic reading as delayed relative to age-appropriate readers. Fair enough, but that characterization leaves open questions about how and why the two groups differ. Is reading skill best viewed as akin to a dedicated process of which skilled readers posses more? How does the absence of a cognitive faculty yield a simple time delay? A dedicated process hypothesis predicts all-or-none differences.

The hypothesis that dyslexia results from impairments in dedicated cognitive mechanisms is difficult to reconcile with our results demonstrating that reading skill falls along a proportional continuum both within the dyslexic and age-matched controls as well as across groups. The distinct process hypothesis predicts that bimodal reading performance distributions should be routinely observed. Instead, the between-group differences in the pronunciation time distributions resembled a self-similar rescaling in their overall shape. This outcome illustrates how the cocktail model allows for theoretically motivated comparisons of performance among groups and individuals. The results also illustrate that the concept of self-similarity allows for a more nuanced and practical understanding of how unskilled reading performance relates to skilled reading performance.

In addition to research implicating cognitive and motor deficits in dyslexia, evidence for impairments in neurobiological factors, brain structures and functions, and even genes are widely reported (e.g., see Pennington, 2009; Fletcher, 2009; Vellutino et al., 2004). Moreover, dyslexia and ADHD share significant comorbidity rates, suggesting that dopaminergic neurophysiology may play a role in dyslexia. Similarly, environmental factors such as poverty, literacy-related activities, and reading instruction (Fletcher, 2009; Vellutino, et al., 2004) are indicated as well. Of course, this list of correlates is far from exhaustive, our goal is simply to illustrate the large and variegated number of causes that are implicated as associated with dyslexia.

We may now return to the hypothesis that a wide variety of sometimes subtle perceptual, cognitive, and neurophysiological deficits are associated with dyslexia. The success of the cocktail model in describing the empirical distributions suggests an explanation for this long-standing empirical pattern. If the exchanges among processes that support neurophysiological, perceptual, and cognitive activities are multiplicative, then apparent deficits in other more or less related cognitive acts that rely on those same basic processes are expected to yield signs of subtly impacted performance. In fact, experimental manipulations contrasting certain easier from more difficult versions of identical cognitive and perceptual acts also reveal rescaling (e.g., see Holden, 2013; Van Rooij, Nash, Rajaraman, & Holden, 2013).

Proportional contingences and interdependence among fast time-scale dynamics, between processes linked to physiological or perceptual states, insure that any low-level impairments will, in turn, propagate into the dynamics of slower time-scale activities such as recognition and articulation (see Holden & Rajaraman, 2012). Our basic proposal is consistent with Goswami's (2011) identification of compromised perception-action entrainment abilities—the *temporal sampling hypothesis*. Similarly, our results suggest that coordination among processes that support performance in children with dyslexia are stretched or dilated in time, relative to controls.

Tasks sharing commonalties or entailing similar complexity in governing the required stimulus-response relations will yield amplified evidence of impairments relative to simpler tasks entailing fewer stimulus-response mappings. For instance, consider the following rough ranking of relative task complexity: The flanker task mapped four potential stimulus options to two response options. Color naming mapped five stimuli to five unique responses. The arithmetic task maps more than 100 potential stimuli to two possible response options. Excepting word naming, the relative ranking of the distribution's location and variability track this loose rank ordering (e.g., see Table 1). Speeded naming, however, requires a unique response for virtually every presented trial. Ostensibly, it is by far the most complex task, at least in terms of the range of potential mappings between presented targets and required responses. However, both groups of participants have extensive practice in reading aloud, relative to that of the other tasks. Thus, historically established constraints—such as coordinative synergies—that arise from learning likely played a more prominent role in the naming task for both groups, and speeded naming ranked only second in terms of relative performance variability for both groups.

In sum, the outcome of our analyses suggests that dyslexia may emerge from low-level perceptual, cognitive, and neurophysiological processes that are not optimized to allow some children to discern and easily retain the complex relationships that must be learned to transition to skilled reading (e.g., see Szmalec, Loncke, Page, & Duyck, 2011). Subtle differences could even reside at the neuronal level. After all, dopamine and related neurotransmitters and neurophysiological pathways are widely implicated in learning and reward.

Diagnosis and remediation

Granting the large difference in reading performance between participants with dyslexia and age-matched controls, there is no obvious categorical distinction that separates the groups. This is an important implication to bear in mind during diagnostic activities. A categorical dyslexia diagnosis will always be somewhat arbitrary. As such, the goal of the assessment should be to determine if a child's reading performance is so impaired and resistant to proven and standard instructional practices that it is legitimate to instate more comprehensive intervention strategies.

We demonstrated that children with dyslexia yield more variable performances than age-matched controls. The reason why skilled readers generated more stable distributions is that they can rely on well-tuned internalized constraints. Learning establishes constraints in the relations among perceptual and cognitive processes, and they narrow the degrees of freedom or range of potential actions (Van Orden, Hollis, & Wallot, 2012). Internalized constraints arise from historically established covariant relations among patterns of spelling, phonology, and linguistic use (Van Orden & Goldinger, 1994).

Appropriate instructional feedback strengthens these constraints; it retunes and stabilizes them across time, thus aiming performance in the direction of fast and accurate pronunciations. Dyslexic readers have difficulty cultivating reliable sources of historical constraint, and their performance entails more competing possible response options. As such, their performances likely yield more incomplete, idiosyncratic or just "wrong" pronunciations. The goal of remediation must be to assist in providing accurate and reliable performance constraints, through augmented instruction, thus reducing the potential to reinforce inaccurate relations. Effective remediation activities do not require a specification of the cause of dyslexia; it does require the identification of the sources of constraint that support skilled readers and that impaired readers lack.

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