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Reading and a Diffusion Model Analysis of Reaction Time

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Abstract

Processing speed is associated with reading performance. However, the literature is not clear either on the definition of processing speed or on why and how it contributes to reading performance. In this study we demonstrated that processing speed, as measured by reaction time, is not a unitary construct. Using the diffusion model of two-choice reaction time, we assessed processing speed in a series of same-different reaction time tasks for letter and number strings. We demonstrated that the association between reaction time and reading performance is driven by processing speed for reading-related information, but not motor or sensory encoding speed.

Keywords

Reaction time; diffusion model; processing speed; the Russian language; reading performance

Introduction

Explaining individual variability in reading performance is presently an active area of research. The current consensus is that phonological awareness, that is, the skill of manipulating sounds of spoken language, substantially predicts variability in reading performance (Blachman, Tangel, Ball, Black, & McGraw, 1999; Bone, Cirino, Morris, & Morris, 2002; Johnson, Pennington, Lee, & Boada, 2009; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1999; Ziegler, et al., 2010). However, the centrality of phonological awareness as the foremost predictive factor has come into question. Arguably, it is neither the only, nor always the best predictor of reading performance (Scarborough, 1998, 2005) and research into phonological awareness in languages other than English suggests that its importance may be overstated, at least for some languages (Share, 2008). Correspondingly, there are concerted efforts to explain variability in reading performance attributable to other cognitive factors, which might be as or more important than phonological awareness in languages other than English (Wimmer, Mayringer, & Landerl, 2000). One such factor is processing speed.

There are numerous studies associating processing speed and reading performance (Bonifacci & Snowling, 2008; Breznitz & Misra, 2003; Shanahan, et al., 2006; Stoodley & Stein, 2006). Yet, despite empirical observations supporting this association, there is little agreement as to why reading performance correlates with processing speed, and whether it

explains variance in reading above and beyond such established predictors as phonological awareness.

The theoretical positions that assert that processing speed does make an important contribution to predicting reading performance distinguish between two broad groups of approaches, a generalized (or general) processing deficit, reflected in *general* slowness of reaction time, characteristic of all (or most) timed or speeded tasks (Nicolson & Fawcett, 1990, 1994; Wolf & Bowers, 1999) and a *specific* deficit (or deficits), reflected in isolated slowness of reaction time, observed predominantly while processing phonological and orthographic (Breznitz & Misra, 2003; Miller-Shaul & Breznitz, 2004) and/or semantic information (Betjemann & Keenan, 2008). The first position, that there is a general underlying speededness deficit, has evolved into the idea that poor reading performance is associated with a general deficit of fluency, automaticity, or procedural learning, and that this deficit underlies all developmental learning disabilities, including reading disability (Fawcett, Nicolson, & MacLagan, 2001; Nicolson & Fawcett, 2006, 2007; Stoodley, Fawcett, Nicolson, & Stein, 2006; Wolf, et al., 2002). Approaches contributing to the second position have not grown into a unified theory because they are predicated on specific deficits (e.g., in phonological, orthographical, or semantic processing) and it is assumed that these deficits also involve weaknesses in processing speed. When exemplified, these approaches encompass ideas about asynchrony in processing speed for phonological versus orthographic information (Breznitz & Misra, 2003; Miller-Shaul & Breznitz, 2004), slowed activation for semantic information in priming tasks (Betjemann & Keenan, 2008), and slowed inhibition of irrelevant semantic information among poor comprehenders (Faust & Gernsbacher, 1996; Gernsbacher & Faust, 1991; Gernsbacher, Varner, & Faust, 1990), among others.

A particular “spin” of the debate between general vs. specific processing speed deficit approaches pertains to the issue of the unique contribution of such deficits to reading performance when established predictors, such as indicators of general cognitive ability (typically captured by IQ or indices of *g*-factor) and/or phonological awareness (or other types of phonological processing) are controlled for (Bonifacci & Snowling, 2008; Stringer & Stanovich, 2000). Three general hypotheses can be formulated with regard to this “spin.”

The first hypothesis, which we will refer to as the “domain-general processing speed hypothesis,” characterizes processing speed as a global domain-general characteristic that is associated with performance on reading as well as non-reading tasks. Thus, all other factors (e.g., age and IQ) being equal, slower individuals will be poorer readers than faster individuals. Evidence in support of this hypothesis comes from the early 1990s, when it was shown that children with reading disability had slower responses on choice reaction time tasks when compared to their IQ-matched peers (Nicolson & Fawcett, 1990, 1994). Further studies have identified associations with reading disability and a range of speeded measures such as balancing and pointing (Stoodley, et al., 2006) and peg-moving (Stoodley & Stein, 2006). The interpretation of these findings is that an underlying processing speed deficit impacts both motor performance and information processing in a nonspecific way.

The second hypothesis, which we will refer to as the “domain-specific processing speed hypothesis,” characterizes processing speed as domain specific. According to this hypothesis, an individual may process more slowly only lexical information and it is that slowness of lexical information processing that results in impaired reading performance. Support for this hypothesis comes from comparisons of performance of good and poor readers on lexical decision and visual and auditory discrimination tasks; in these tasks processing speed was captured both by ERP latency and reaction time measures (Breznitz, 2002; Breznitz & Misra, 2003; Miller-Shaul & Breznitz, 2004). It was reported that poor readers exhibit significantly slower reaction times and delayed ERP components for high-

level lexical tasks (e.g., lexical decision), but not for low-level perceptual tasks (e.g., auditory tone or visual line discrimination). These results support a domain specific interpretation of processing speed, where low-quality lexical representations lead to slow and impaired reading performance (Perfetti, 2007; Perfetti & Hart, 2002) that is not generalizable to other domains.

The third hypothesis, which we will refer to as the “no direct association hypothesis,” posits that processing speed may only be associated with reading performance through a link with IQ. Thus processing speed predicts variability in reading performance when the former is the only predictor of the latter, but this shared variance is extinguished when the prediction is controlled for IQ. Consequently, processing speed is associated with reading performance not directly, but indirectly, because both processing speed and reading performance share some common variance with IQ. Research investigating the shared variance among reaction time, word, and nonword reading found that the relationship was almost totally attributable to phonological awareness (or other indicators of phonological processing) and IQ (as captured by subtests of the WAIS-R, Wechsler, 1986). It was concluded that reaction time does not contribute any additional information to explaining variance in reading performance (Stringer & Stanovich, 2000), at least in college students exhibiting a range of reading ability. Recently, researchers (Bonifacci & Snowling, 2008) compared reaction time differences among children with reading disability, children with low IQ, as captured by the WASI (Wechsler, 1999) and an Italian version of the KBIT (Kaufman & Kaufman, 1990), and typically developing children. Reaction time was slower in children with low IQ, as expected from the literature on the link between general cognitive ability and reaction time, but not significantly different between children with reading disability and their typically developing peers. It was again concluded that there was no general processing speed deficit associated with reading disability, making processing speed “uninteresting” as a predictor of individual differences in reading performance.

These three hypotheses vary on the generality versus specificity of the relationship between reading performance and processing speed; each makes specific predictions about the relationship between the two (i.e., processing speed and reading performance) under a range of conditions (e.g., whether a processing speed task makes reading demands, whether the data are analyzed while controlling for the effects of general cognitive ability, and so forth).

This simple characterization of the state of the field belies its variability and the complexity of individual studies. Yet all, or almost all, relevant studies capitalize on the following observations: (1) there is a modest-to-substantial relationship between reading performance and processing speed, however measured; (2) there is a very well replicated relationship between processing speed and general cognitive ability, however measured; (3) there is a well established link between reading performance and general cognitive ability. In addition, all, or almost all, relevant studies ask why reading performance correlates with processing speed. These studies, by virtue of being aligned with the different hypotheses presented above, have different answers to this question. The “domain-general processing speed hypothesis” makes claims that there are general sensorimotor fluency and automaticity deficits that lead to slower processing speed in general and poor reading performance in particular. Thus, slow processing speed in both reading-related (e.g., a speeded letter discrimination task) and reading-unrelated (e.g., a speeded number discrimination task) tasks should be associated with poor reading performance. The “domain-specific hypothesis” predicts that the relationship between reading performance and processing speed depends on the extent to which the latter recruits reading-related information. Thus, poor performance on a letter discrimination task should be associated with reading, but poor performance on a number discrimination task, should not. Finally, the “no direct association hypothesis” predicts that any processing speed task will show association with reading skill, but that this

association will reflect only shared variance with the general cognitive ability. Thus, any correlation between processing speed and reading performance will be nullified when controlling for the level of general cognitive ability. In this study we compare these three hypotheses to elucidate the understanding of the relationship between processing speed and reading performance.

Study Objectives

In prior studies, processing speed has been overwhelmingly assessed by recording response times, but it is now accepted that response times are the outcome of multiple processes, reflecting motor, information processing, and decision components. Mean reaction time conflates these components and may not present an accurate picture of processing speed. More concerning is the possibility that the interaction of various components of reaction time may differ between individuals, such that two individuals have the same mean reaction time, but may have arrived to this point with very different profiles of motor, information processing, and decision components.

We used the diffusion model of two-choice reaction time to decompose indicators of processing speed obtained in a series of reaction time tasks to investigate the association between processing speed and reading performance. The diffusion model of reaction time (Ratcliff & McKoon, 2008) is one of several theoretical models of how reaction times emerge from a set of interacting components. Specifically, the model assumes that, at the start of a trial, sensory components encode the stimulus. Following sensory encoding, information accumulates to one of two decision boundaries. When the information accumulation process reaches a boundary a response is initiated and motor components account for the remaining time in the trial. Thus, the total time for a response is the time taken for sensory encoding, for information accumulation to reach a decision boundary, and for the execution of a motor response (WebFigure 1, <http://www.yale.edu/eglab/publications.html>, displays this process). By decomposing reaction time in this manner, we can explicitly compare general sensory and motor processing speed (non-decision time or NDT), and specific information processing speed (information accumulation or IA) on a reaction time task. Furthermore, by decomposing the reaction time distributions we remove the influence of decision processes on processing speed. A strategy of slow and accurate responding or fast and inaccurate responding, that would have a significant impact on mean reaction time, is separated from sensorimotor and information processing speed.

This study had two objectives: (1) to determine what components of reaction time, when decomposed as put forth by the diffusion model, contribute to reading performance and whether these contributions are criterion-general (i.e., present in both reading-related and unrelated tasks) or criterion-specific (i.e., limited to reading-related tasks only); and (2) to establish whether these components, collected across reading-related and unrelated tasks, contribute unique variance in the presence of indicators of phonological processing and the general cognitive ability.

To determine what components of reaction time contribute variance to reading skill we compare estimated parameters from the diffusion model and their respective mean reaction times to several indicators of reading performance. In the context of the diffusion model, it is assumed that the mean reaction times may obfuscate the underlying components of the reaction time task. By decomposing reaction time we can differentiate between the two general theoretical approaches to the empirically registered association between indicators of processing speed and reading performance. Specifically, according to the domain-general processing speed hypothesis, we should see connections between reading performance and

indicators of general speeded process, which would be reflected by correlations with both the NDT and IA parameters, and with both reading-related (e.g., letter) and reading-unrelated (e.g., number) tasks. On the contrary, as per the domain-specific processing speed hypothesis, the association between indicators of reading performance and processing speed should be limited only to IA parameters and only to reading-related (e.g., letter) tasks. Hence, according to the two hypotheses, we can compare the contributions of NDT and IA; the former is presumably domain general, possibly reflecting the motor fluency and automaticity processes that are responsible for reading disability in the models put forth by Nicolson and Fawcett (2007), whereas the latter is thought to reflect domain-specific processes similar to those proposed by Breznitz and colleagues (Breznitz, 2002; Breznitz & Misra, 2003; Meyler & Breznitz, 2003). We favor the latter approach and hypothesize that the predictor- (i.e., IA) and criterion- (i.e., letter-discrimination) specific indicators are associated significantly (or associated significantly better) with indicators of reading performance, compared to other reaction time indicators.

To establish the uniqueness of the contribution of reaction time, we collected measures of general cognitive ability (IQ), indicators of phonological processing (phonemic awareness and serial rapid naming), and other reading-related indicators (single word identification, single pseudoword reading, and comprehension of connected text). As per the discussion above, among domain-general, domain-specific, and no direct association explanations, we favor the domain-specific direct assumption and hypothesize that the IA indicator obtained through reading-related (i.e., letter discrimination) tasks will account uniquely for a portion of variance in reading performance over and above that accounted for by indicators of general cognitive ability and phonological processing.

Method

Participants

The sample included children attending third, fourth, and fifth grades in public schools in a middle-size city in the Russian Federation. Concerns have been raised in the literature that significant differences between groups may be attributable to only a few individuals in one or another group, particularly when comparing groups of individuals with and without reading disability (Heath, Bishop, Hogben, & Roach, 2006; Roach, Edwards, & Hogben, 2004). Because comparison of group means may exaggerate group differences, this sample constituted a normative community-based sample; individuals were not selected for reading difficulties. The sample included 188 children: 98 boys and 90 girls, aged 7–12 (mean = 9.43, *sd* = .88).

Materials

All materials were presented in Russian. All assessments utilized in this work have been previously utilized with Russian-speaking samples, are stated to have adequate psychometric properties, and have been published or are in press in English-language journals (see specific references below).

Reaction time—Participants completed four “same-different” reaction time (RT) tasks (WebFigure 2, <http://www.yale.edu/eglab/publications.html>). Stimuli were pairs of letter or number strings (6 items per string, random combinations of letters and numbers; of note is that as Russian permits combinations of consonants that can extend to 4 letters, most letter combinations in Russian are pronounceable) presented simultaneously in one task and successively in the other; the strings were prearranged, but presented at random. Two modes of presentation (simultaneous and successive) were used to both maximize the reliability of the assessment by measuring the same construct multiple times and to minimize the

boredom factor by alternating the formats of the presentation. The strings were administered on a computer screen using E-Prime software. Items were organized in blocks. Each block contained 16 unique “same” (i.e., two strings are the same) and 16 unique “different” (i.e., two strings are different) items, 32 items altogether. Each participant saw 4 blocks per session, so that items were randomized within blocks. Participants each completed 128 items for each session. Within each session, items were presented either simultaneously, with both stimuli on the screen at the same time, or successively, with one stimulus followed immediately by the onset of the second stimulus. Moreover, sessions varied, so each session contained only digits or only letters. Thus, there were 4 unique sessions (simultaneous vs. successive and digits vs. letters). Each session was presented twice, with the majority of children completing 8 sessions. For reliability purposes, each child was assessed on two different occasions, 6–8 weeks apart. Thus, each child was assessed twice, and saw 256 unique items (half letters and half numbers). Each assessment contained four sessions, and each session included 4 blocks of 32 trials. Participants were asked to press the ‘z’ key if the stimuli were the same and the ‘/’ key if they were different. The task ended after the participant completed all 8 sessions, 128 items each. Reaction times longer than 3 seconds were not collected and those shorter than 300 ms (below the 2nd percentile) were trimmed from the data set when calculating means, but retained for the diffusion model parameter estimations (Ratcliff, 1993).

Reading performance—Reading performance was captured through a number of indicators. First, at the single-word level, children’s skills of word identification and pseudoword decoding were assessed. Second, at the level of connected text, children’s comprehension skills were evaluated. Finally, aspects of children’s phonological processing were assessed with two tasks, a phonological awareness task, and a rapid naming task. These tasks were introduced to capture variability in processes that are thought to, at least in part, underlie reading variability in Russian (Grigorenko, et al., 2007; Grigorenko, Kornev, & Rakhlin, in press; Kornev, Rakhlin, & Grigorenko, 2011; Naples, Chang, Katz, & Grigorenko, 2009).

Word identification (WId): Children were presented with a list of 18 real words, one by one, and asked to sound these words out. The words ranged from 2 to 5 syllables in length. The number of errors was used as an indicator of the skill of word identification (Grigorenko, under review). The internal consistency of the word identification measure in this sample was 0.79.

Pseudoword Decoding (PWDe): Children were presented with a list of 15 pronounceable pseudowords, one by one, and asked to sound these words out. The words ranged from 1 to 5 syllables in length. The number of errors was used as an indicator of the skill of pseudoword decoding (Grigorenko, under review). The internal consistency of the decoding measure in this sample was 0.79.

Comprehension (Co): Comprehension was assessed by overlapping sets of 11 connected text paragraphs with 43 comprehension questions. Participants read a series of age-appropriate paragraphs and were asked questions probing test content. We counted the number of correct responses. These paragraphs have been previously used in research whose results were published (Grigorenko, et al., 2007). The internal consistency of the comprehension scale in this sample was 0.75. Standardized comprehension scores were computed using item-response-theory-based approaches (Mair & Hatzinger, 2007; Smith & Smith, 2005).

Phonemic Awareness (TAAS): Phonemic awareness was assessed with a Russian modification (Naples, et al., 2009) of Rosner's Test of Auditory Analysis Skill (TAAS, Rosner, 1999). Participants are required to make a new word by deleting a specified element (e.g., "Say meat. Now say it again, but don't say m"). The trial items and the first few test items involve the deletion of a morpheme in a compound word or a syllable in a two-syllable word. The 40 remaining items involve omitting a phoneme, first in the initial position, then at the end of a word, then from consonant blends at the beginning of a word, and finally from phoneme blends in the middle of a word. The items varied in length from 1 to 4 syllables. The internal consistency of the TAAS in this sample was 0.82.

Rapid Automatized Naming (RAN): We used a Russian version (Naples, et al., 2009) of the Test of Rapid Naming for Colors, Objects, Numbers, and Letters (Denckla & Rudel, 1974, 1976a, 1976b) to assess another aspect of phonological processing, serial automatized naming. Each of the four tests of the RAN consists of a chart containing five different items (e.g., five colors or five letters) presented in horizontal rows of 10 items each, repeated in a random order. The time it takes the child to name the 50 items from left to right, top to bottom, is measured. For our analysis we used the mean of the 4 tests.

General cognitive ability

Intelligence (FI and VI): These assessments have been previously used in Russia (Grigorenko & Sternberg, 2001). Fluid intelligence (FI) was measured with two subtests of a test of nonverbal intelligence, the Test of g: Culture Fair, Scale 2 (Cattell & Cattell, 1973) —a test of fluid ability designed to reduce, as much as possible, the influence of verbal comprehension, culture, and educational level. For the first subtest, we used Series, in which individuals were presented with an incomplete, progressive series of figures. The participants' task was to select the answer that best continued the series from among the choices provided. For the second subtest, we used the Matrices subtest, in which the task was to complete the matrix presented at the left of each row. The internal consistencies of the FI scales in this sample were 0.64 and 0.60, respectively. The test of verbal intelligence (VI) was adapted from existing traditional tests of analogies and synonyms/antonyms used in Russia. The first part of the test included 20 verbal analogies. An example is *shoe : foot = hat : (a) coat, (b) nose, (c) see, (d) head*. The second part included 40 pairs of words, and the participants' task was to specify whether the words in the pair were synonyms or antonyms. Examples are *cold : hot* and *calm : quiet*. The internal consistencies of the VI scales in this sample were 0.74 and 0.81, respectively.

Results

In line with Stringer and Stanovich (2000) we analyzed the data at the individual level with the goal of explaining variability in measures of reading performance. Accuracy and reaction time for all of the 16 sessions (8 sessions per time occasion) were used to generate diffusion model estimates; only correct responses were used to calculate the mean RT. Diffusion estimates were generated for each child and condition using the fast-DM software (Voss & Voss, 2007, 2008). This software is design to degenerate parameter estimates for Ratcliff's (1978) diffusion model. A diffusion-model data analysis is based on the distributions of both correct and erroneous responses from a binary decision task. In turn, from these distributions a set of parameters estimates for the underlying cognitive processes are produced (Voss, Rothermund, & Voss, 2004). In general, fast-DM uses the partial differential equation (PDE) method (Voss & Voss, 2007) to compute the predicted cumulative distribution function (CDF) and the Kolmogorov-Smirnov statistic (Voss, et al., 2004) for parameter optimization. That is, as described by the authors of the software (Voss & Voss, 2007, pp. 768–769), first, the maximal vertical distance of the predicted and the

empirical cumulative response-time distribution (i.e., the KS test statistic) is minimized. Second, to get a single optimization criterion, the response time distributions from both thresholds are merged into one distribution by equipping all reaction times from the lower threshold with negative signs while using positive signs for the times from the upper threshold. Of note is that the CDF of the resulting combined distribution conserves the original shapes of the individual distributions, the ratio of errors is represented as the value of the combined CDF at time zero. Third, to estimate the model parameters a multidimensional search is conducted, using a version of the simplex downhill method (Nelder & Mead, 1965) to optimize the fit.

For the data presented here, models were fit that allowed for separate information accumulation (i.e., drift) estimates for “same” and “different” conditions. However, non-decision was estimated across both conditions (i.e., for “same” and “different” combined). Altogether, there were three diffusion model estimates for each of the four sessions (8 for drift and 4 for non-decision, 12 parameters in total). Mean RT was calculated for “same” and “different” conditions for each of the 4 sessions (i.e., 8 indicators altogether). Specifically the RT data were modeled as follows. For each participant and condition (same/different, letter/number) a file was generated that contained data on every trial; specifically, accuracy, condition and reaction time. These files were then used as input to the fast-DM software which estimated the parameters of the diffusion model separately for each file. Thus for each file representing a participant by condition pairing a full set of parameter estimates were calculated, with all parameters being invariant across conditions with the exception of “drift” (referred to here as IA information accumulation), which varied for ‘same’ vs. ‘different’ responses. The distributions of mean reaction times, IA, and NDT were approximately normal, e.g., they were unimodal, did not exhibit substantial skewing, or floor or ceiling effects. Descriptive statistics are shown in WebTable 1 at <http://www.yale.edu/eglab/publications.html>.

Which Processing Speed Components of Reaction Time Share Variance with Reading Performance?

First, pairwise correlations and hierarchical regression analyses were used to determine which processes estimated by the diffusion model most strongly correlated with reading performance, and how the different diffusion model parameters relate with mean reaction time. For the information accumulation (IA) parameters, the range of correlations with the mean RT was $-.31$ – $.49$ (mean = $.05$ and median = $.06$). However, for the non-decision time (NDT) parameters, the range of correlations with the mean RT was $.80$ – $.87$ (mean = $.83$ and median = $.83$). These results show that the mean RT primarily reflects the variance associated with encoding time and motor responses (i.e., NDT), rather than the variance associated with IA parameters (see WebFigure 3, <http://www.yale.edu/eglab/publications.html>).

Second, we wanted to investigate the associations among RT indicators and indicators of reading performance, reading-related processes, and general cognitive ability. The results of these analyses are reflected in Figure 1, presenting density plots of correlations between reading measures and IA, NDT, and mean RT, when these measures are obtained across simultaneous and successive modes of letter and number strings combined (for differences in correlations for successive and simultaneous modes of presentation for letter and number strings, see WebFigure 4, <http://www.yale.edu/eglab/publications.html>). These plots represent the correlations of all of the indices of IA, NDT, and mean RT, obtained in successive and simultaneous modes for same and different conditions for letter and number strings, i.e., 8 correlations each. The results in Figure 1 suggest that IA consistently shows higher correlations with indicators of reading performance (primarily word identification—WId and pseudoword decoding—PWDe, but also comprehension—Co). The ranges, means,

and medians of corresponding correlations were .00–.34, .19, .19; .09–.34, .21, .18; and .07–.26, .19, .21, respectively. The NDT parameters and mean RT parameters demonstrated lower correlations (ranges, means, and medians of corresponding correlations for NDT and mean RT were .04–.16, .10, .09 and .01–.18, .09, .09; .03–.15, .11, .13 and .07–.14, .11, .11; and .01–.16, .07, .05 and .01–.19, .09, .10, for word identification—WId, pseudoword decoding—PWDe, and comprehension—Co, respectively). The pattern of correlations with reading-related measures (TAAS and RAN) also demonstrated stronger associations with IA than with NDT or mean RT (ranges, means, and medians for IA, NDT, and mean RT were .03–.42, .26, .27 and .01–.45, .29, .32; .06–.18, .12, .11 and .02–.21, .11, .11; and .01–.23, .13, .14 and .06–.25, .15, .15, for TAAS and RAN, respectively). Of note is that the correlations were comparable for TAAS and RAN, even though the latter is also a timed indicator. The advantage of IA over NDT and mean RT was less pronounced, but also present for correlations with VI and FI (ranges, means, and medians for IA, NDT, and mean RT were .01–.32, .17, .18 and .10–.23, .16, .16; .03–.12, .07, .07 and .01–.15, .09, .10; .01–.20, .08, .08 and .00–.20, .11, .10, for VI and FI, respectively). Thus, IA predicted a greater amount of variance in reading performance than either NDT or mean RT, but there was virtually no difference among IA, NDT and mean RT in relation to fluid intelligence, lending some support for a *g* component in reaction time, but one that does not correlate with reading achievement. Thus, our hypothesis with regard to the first objective of the study was confirmed: the predictor- (i.e., IA) and criterion- (i.e., letter-discrimination) specific indicators appeared to be associated with indicators of reading performance to a higher degree, compared to other indicators of RT (NDT and mean RT). On average, the magnitude of the correlations with IA was about twice the magnitude of the correlations with mean NDT and mean RT (i.e., the mean and median correlations for all reading-related measures were .23 and .23; .10 and .10; and .11 and .12 for IA, NDT, and mean RT, respectively). Specifically, when the patterns of correlations for IA, NDT, and mean RT were compared to each other by means of establishing the difference between dependent r 's via the Fisher z' (Cohen & Cohen, 1983), they were consistently different for indicators of reading performance (WId, PWDe, and Co), phonological processes (TAAS and RAN), and general cognitive abilities (VI and FI) for IA vs. NDT (52% of all correlations) and IA vs. mean RT (54% of all correlations), but not NDT vs. mean RT (21% of all correlations).

In order to compare the relative contributions of processing speed (IA, NDT, and mean RT), phonological processing (TAAS and RAN), and intelligence indicators (VI and FI) to reading performance we selected the “best” speed of processing variables. This decision was made in order to reduce the number of variables and the degree of co-linearity in the final regression equations. To select the “best” indicator for RT, a set of hierarchical regression analyses was completed in which we compared the predictive power of diffusion model parameters IA and NDT, as well as mean RT in predicting reading performance. Given that all RT measures were sampled from simultaneous and successive presentations of letters and numbers, the RT measures were entered in blocks: first the indicators for letters and then for numbers. The results of these analyses are shown in Figure 2.

As expected from the pairwise correlations (see Figure 1), information accumulation was the most predictive variable. Figure 2 demonstrates the differential predictive power for indicators of processing speed. Specifically, neither mean RT nor NDT indicators contributed significant variance to the criterion variables in the regression models. However, the IA indicators were statistically significant for both letters and numbers for decoding ($R^2 = .13$, $p < .001$ and $R^2 = .08$, $p < .005$, respectively) and word identification ($R^2 = .16$, $p < .001$ and $R^2 = .11$, $p < .005$, respectively), and for comprehension only letters contributed significantly ($R^2 = .16$, $p < .001$). To summarize, in predicting variability in reading performance, indicators of IA, especially IA in the letter conditions, appear to be most

informative. These four estimates of IA (for successive and simultaneous presentation and same and different, letters only) were used in subsequent regression analyses (Table 1).

Is There Unique Variance Shared between Speed of Processing and Reading Performance?

To determine whether processing speed contributes unique variance to reading skill in the presence of intelligence and phonological awareness we conducted a series of hierarchical regressions and commonality analyses. The hierarchical regressions determined how much variance in reading performance was explained, and whether processing speed contributed enough variance, after the inclusion of intelligence and phonological processing, to introduce a statistically significant change in R^2 . The commonality analysis decomposes explained R^2 into subsets of predictor variables indicating the extent to which the variables in the regression equation share variance with the criterion variable one by one and in combination (Nimon, Lewis, Kane, & Haynes, 2008; Seibold & McPhee, 1979). The results of the regression analyses are presented in Table 1, and the results of the commonality analysis are presented in Table 2 (also see WebFigure 5, <http://www.yale.edu/eglab/publications.html>).

As anticipated, the total R^2 (s), as shown in Tables 1 and 2, are identical (i.e., .341 vs. .341, .171 vs. .171, and .235 vs. .235). Also, as anticipated, the results of the commonality analyses support the findings from the regression analyses, but further them. For all three dependent measures of reading performance (WId, PWDe, and Co), IA contributes modest but significant unique variance, with the larger contributions being associated with word identification, WId (9.5%, i.e. 55.67% of 17.1%) and the smallest (2.4%, i.e. 7.04% of 34.1%)—with comprehension, Co. IA also shares variance with other variables in the equation while contributing to the variance in comprehension, word identification, and decoding. These shared contributions are mostly with phonological indicators (with TAAS and RAN combined, 3.2% for Co, 5.6% for WId, and 7.6% for PWDe), but also with intelligence (1.8% for Co and near-zero percent for WId and PWDe). Indicators of phonological processing (RAN and TAAS) contribute to all variables, but their contributions are much more substantive for pseudoword decoding (PWDe) and comprehension (Co), 9.0% and 9.6%, respectively, than for word identification (WId)—.8%. Such low contribution to WId might be explained by the fact that the skill of decoding (i.e., sounding out words), unlike the skill of spelling (i.e., writing words down) is much easier in Russian than in English. By grade three (and our sample includes children in grades 3–5), it is expected that decoding skills of typical words is mastered, although there still might be difficulties with decoding unknown words or pseudowords. The contribution of intelligence indicators is also variable: from 7.5% to comprehension to 1.5% and 1.3% to word identification (WId) and pseudoword decoding (PWDe), respectively. Finally, perhaps surprisingly, the common contribution of all indicators (when unique variance is accounted for) is rather low, near zero for word identification (WId), 2.3% for pseudoword decoding (PWDe), and 4.6% for comprehension (Co). In sum, IA estimates of the diffusion model appear to contribute to indicators of reading performance uniquely and separately from phonological processing and general cognitive functioning. Moreover, the regression and commonality analyses especially favored IA indicators obtained from reading-related (i.e., letter discrimination) tasks, supporting our hypothesis for the second objective of this study.

Specifically, the letter IA block contributed statistically significantly and independently to the variability in all measured indicators of reading performance (the range of incremental R^2 is 10%–17%), when entered first into the regression equation. When entered last, IA added incrementally only to WId (9.7%, $p < .01$), with its contributions to PWDe and Co being borderline (1.5%, $p = .14$ and 2%, $p = .19$, respectively). Additionally of interest is that, the contributions of intelligence indicators appeared to be smallest for decoding, PWDe

(1%–3%) and largest for comprehension, Co (7%–8%), with word identification, WId, in between (5%–7%). Finally, indicators of phonological processing appeared to explain a substantial portion of variance (10%–15%) in pseudoword decoding, PWDe, and comprehension, Co, but not in word identification, WId. These findings suggest, that speed of processing is “psychometrically interesting” in that it provides a small, although significant and unique contribution to variance in reading performance.

Discussion

In this study we registered a set of indicators and then decomposed performance on a set of same-different reaction time tasks for letter and number strings using the diffusion model of choice reaction time (Ratcliff & McKoon, 2008). Our goal was to compare three hypotheses that attempt to explain the relationship between processing speed and reading performance. These hypotheses assume, respectively, that (1) processing speed is a general characteristic of cognition, and deficits in it are associated with difficulties in reading as a cognitive process (Nicolson & Fawcett, 2007; Shanahan, et al., 2006); (2) there are domain-specific information processing deficits (Breznitz & Misra, 2003; Miller-Shaul & Breznitz, 2004) that are associated with difficulties in reading performance; or (3) there is no causal or other meaningful relationship between processing speed and reading performance (Bonifacci & Snowling, 2008; Stringer & Stanovich, 2000). Achieving our goal, we met the two objectives of this work: to decompose RT and identify the facet related to reading performance; and to investigate whether that RT facet possesses a predictive power of reading performance over and above such established predictors of reading performance as phonological processing and IQ. In addition, we confirmed our hypotheses that only a particular facet of RT, registered in the context of lexical processing (i.e., letter discrimination), predicted reading performance.

The parameters estimated by the diffusion model appear to clarify the picture of the relationship between reading performance and processing speed. Our results showed that the relationship existed and was driven by information accumulation (IA), but not by sensory and motor components (NDT) of processing. This finding challenges theories of motor speed as a causal factor predicting individual differences in reading skill. Converging support for our findings comes from a previous study from our group (Katz & Wicklund, 1971) and another recent study of typically developing and reading disabled individuals on a lexical decision task (Snellings, et al., 2009). In the latter, similar to the results presented here, after decomposing lexical decision response time data, it was found that the groups of typical and disabled readers differed significantly on estimates of IA but not motor or sensory processes. Of note also is that Snellings and colleagues (2009) fit their diffusion model using a different procedure, the DMAT toolbox in Matlab (Vandekerckhove & Tuerlinckx, 2008), which is an alternative to what we used; this suggests that neither their nor our results were statistical artifacts of the estimation process.

Additionally, IA for letters contributed significantly more than IA for numbers, indicating that the relationship is specific to the information being processed (i.e., lexical information); that is, letters are more related to reading expertise than are numbers. These findings are consistent with domain specific accounts of reading performance, specifically, that the speed of processing for lexical information, not any other information, coincides with reading performance (Breznitz, 2002; Breznitz & Misra, 2003; Meyler & Breznitz, 2003). These accounts interpret processing speed not as a general characteristic of cognition, but as a reflection of the quality of lexical representation (Perfetti & Hart, 2002). Higher quality lexical representations are activated more rapidly, leading to better performance on word (or pseudoword) decoding and comprehension tasks, and faster performance on behavioral and electrophysiological measures. Finally, our results show that speed of processing, as

measured by IA, contributes unique variance to reading performance when controlling for more established predictors of reading such as intelligence or phonological processing. Importantly, this relationship is only present and detectable when reaction time is decomposed into component processes.

The findings of Stringer and Stanovich (2000) and Bonifacci and Snowling (2008) are not incompatible with these results as both these studies used mean reaction time as an indicator of processing speed. Given that mean RT behaves more like NDT than IA, the association between RT and reading performance was masked by the usage of mean RT. Moreover, it is important to recognize that specific indicators of IQ (e.g., Wechsler tests of intelligence) include processing speed in their cumulative indicators, thus, possibly masking the present, but not strong, relationship between processing speed and reading.

Similarly, our results are also compatible with findings for general speed of processing theories of reading disability that used mean reaction time as an indicator of processing speed. The parameter estimates of the diffusion model separate information processing, and sensorimotor processing speed, but mean RT conflates the two variables, which might explain the inconsistent findings in the literature.

Our results contribute to the body of research investigating the relationship between reading performance, indicators of intelligence and processing speed by clarifying the specifics of this relationship. They also further the significance of considering predictors of reading other than phonological awareness (Wolf, et al., 2002) and stress the importance of considering the relationships between various “predictor” variables longitudinally, acknowledging the changing developmental dynamics of their covariation and contribution to reading. Thus, it is possible that at the early stages of reading acquisition, ubiquitous indicators of processing speed are important, but their subsequent contribution is differentiated by experience and practice, so that at later stages of reading mastery only the speed of processing for lexical information remains relevant.

Our work is not without limitations. First, our sample was composed of typically developing children speaking and reading Russian, while the majority of similar research has been conducted in English, and with individuals ascertained for reading difficulties. Correspondingly, more research is needed both in Russian and English to extend and verify our findings. Secondly, we restricted speed of processing to a reaction time task. Reaction time is the most used task, but certainly not the only one. Similarly, we included only letter and number tasks. Indicators of processing speed in other domains of cognitive functioning should also be investigated. Thus, whereas our results are promising, there is need for replication and verification of our findings.

Overall, our results challenge both “all-or-nothing” hypotheses; that speed of processing is a general sensorimotor characteristic that explains variance in reading performance or that speed of processing is a psychometrically uninteresting construct that shares variance with established predictors such as intelligence or phonological awareness, but has no meaningful association with reading performance. Instead, our findings suggest that processing speed for reading-related (i.e., information accumulation for letter strings) information explained unique variance in reading performance, but sensory and motor processing speed contributed virtually nothing to reading. Our data appear to resolve some of the inconsistencies previously observed in the field. We show that only certain indicators of RT contribute to the variance in reading performance; these indicators arise from a realistic modeling of RT, without reducing its complexity to a simple mean time indicator. Moreover, we showed that it is RT registered in the context of lexical processing that is relevant to reading. Thus, speed of processing is associated with variability in reading

performance; it is neither the only factor, nor is it irrelevant. The next step is to determine *why* it matters.

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Figure 1.

Correlation density plots for indicators of word identification (WId), pseudoword decoding (PWDe), comprehension (Co), phonemic awareness (TAAS), rapid naming (RAN), verbal (VI) and fluid intelligence (FI), indicators of diffusion model (IA and NDT), and mean RT. Density plots were created using the GGPlot2 package in the R programming language (R Development Core Team, 2009; Wickham, 2009). Absolute values of all correlations between diffusion and RT measures and achievement measures were graphed using the default Gaussian density estimation routines in R, and scaled to have equal heights for ease of visualization.

Figure 2.

Explained variance for reading performance measures by RT indicators. Co: Comprehension, WId: Word Identification, PWDe: Pseudoword Decoding, IA: Information Accumulation (signifies a block of 4 indicators, for successive and simultaneous presentation and same and different, letters only), NDT; Non-Decision Time, Mean: Mean reaction time. Bars indicate adjusted R^2 for regression models including only mean RT, NDT or IA as predictors of achievement measures. Bars are in groups of three with the first bar reflecting indicators from only 'letter' conditions, the second only 'number' conditions, and the last both 'letter' and 'number' conditions.

Table 1

Results of Hierarchical Regression Analyses Predicting Variation in Indicators of Reading Performance

Predictor	Co(p)			
	R^2	ΔR^2	R^2	ΔR^2
IA	0.109(.00) ₁		0.341(.00) ₃	.020(.19)
TAAS & RAN	0.263(.00) ₂	.154(.00)	0.332(.00) ₂	.129(.00)
VI & FI	0.341(.00) ₃	.078(.00)	0.203(.00) ₁	
	WId(p)			
	R^2	ΔR^2	R^2	ΔR^2
IA	0.166(.00) ₁		0.171(.00) ₃	.097(.00)
TAAS & RAN	0.165(.00) ₂	-.001(.38)	0.074(.00) ₂	.082(.00)
VI & FI	0.171(.00) ₃	.051(.22)	-0.008(.69) ₁	
	PWDe(p)			
	R^2	ΔR^2	R^2	ΔR^2
IA	0.131(.00) ₁		0.235(.00) ₃	.015(.14)
TAAS & RAN	0.229(.00) ₂	.098(.00)	0.220(.00) ₂	.189(.00)
VI & FI	0.235(.00) ₃	.006(.23)	0.031(.03) ₁	

Note. Subscripts indicate order of block in regression equation. Co: Comprehension, WId: Word Identification, PWDe: Pseudoword Decoding, IA: Information Accumulation, TAAS: Test of Auditory Analysis Skill, RAN: Rapid Automatized Naming

Commonality Analyses for the Contributions of Phonological Awareness, Intelligence and Information Accumulation

Table 2

	FI&VI	FI,VI, & TAAS & RAN	TAAS & RAN	TAAS, RAN & IA	IA	FI,VI, & IA	Common	Total
Co	21.92	14.57	28.22	9.41	7.04	5.25	13.59	34.1
WId	8.92	-0.99	4.68	32.93	55.67	-2.37	1.21	17.1
PWDe	5.32	1.34	38.13	32.14	12.36	1.10	9.64	23.5

Note. Values indicate percentage of explained R^2 . Co: Comprehension, WId: Word Identification, PWDe: Pseudoword Decoding, IA Information Accumulation, TAAS Test of Auditory Analysis Skill, RAN Rapid Automatized Naming, Common: Explained variance common to all predictor variables. Total: R^2 -matching those obtained by means of the regression analyses (see Table 1).