Intensive summer intervention drives linear growth of reading skill in struggling readers

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Abstract

An achievement of reading research has been the development of intervention programs for struggling readers. Most intervention studies employ a pre-post design, to examine efficacy, but this precludes the study of intervention-driven growth. Determining the time-course of improvement is essential for cost-effective, evidence-based intervention decisions. The goal of this study was to (a) analyze reading growth curves during an intensive summer intervention program and (b) characterize factors that predict individual differences in growth. A cohort of 37 children (6-12y) with reading difficulties ($N = 21$ with dyslexia diagnosis) were enrolled in 160 hours of intervention. We collected behavioral measures over 4 sessions assessing decoding, oral reading fluency, and comprehension. Data were analyzed using mixed-effects modeling to characterize growth and the moderating effect of individual differences (age, IQ, phonological awareness, & initial reading skill). Longitudinal measurements revealed a linear dose-response relationship between hours of intervention and improvement in reading ability. Decoding skills showed substantial growth (Cohen's $d = 0.81$ (WJ Basic Reading Skills)), with fluency and comprehension growing more gradually ($d = 0.35$ (WJ Reading Fluency)). Multivariate analyses revealed a significant contribution of initial reading ability in predicting individual growth rates: This demonstrates the efficacy of intensive intervention for highly impaired readers.

Introduction

The most common learning disability in school-aged youth, developmental dyslexia, affects between 5-17% of children (Wolf, 2007). Grounded in impaired decoding skill, dyslexia is characterized by disproportionate impairment in reading ability in comparison to other cognitive abilities (S. E. Shaywitz, Morris, & Shaywitz, 2008). Due to its high incidence, and the non-trivial impact on long-term academic achievement (National Assessment of Educational Progress, 2006; Raskind & Goldberg, 1999), a large body of scientific research has focused on the development of effective treatments for developmental dyslexia. Research starting in the 1980s has concluded that an effective intervention curriculum (a) explicitly teaches phonological awareness (Ehri et al., 2001; Slavin, Lake, Davis, & Madden, 2010; Torgesen, 2006; Wagner & Torgesen, 1987), (b) starts early at a child's first indication of struggle (National Reading Panel, 2000; S. E. Shaywitz et al., 2008; Torgesen, 1998; Wanzek et al., 2013), and (c) is multi-componential in nature layering in training in strategy, orthography, morphology and fluency (Lovett et al., 2008; Morris et al., 2012; Stevens, Walker, & Vaughn, 2016; Wanzek & Vaughn, 2010).

Beyond the efficacy of different curricula, important questions are left unanswered by previous research. Although the importance of phonology in training is clear, and the messages of supplementing that foundation with broader fluency training is now widely accepted (Lovett et al., 2008; Morris et al., 2012), the question remains about how interventions can be tailored to an individual's specific need. For example, is there a point when additional phonics training is no longer productive, and supplementary training methods should be enhanced? Or, more generally, how might we decide when there are diminishing returns for more hours of intervention? A substantial amount of research has been done to develop successful treatments, and determine the

efficacy of different treatment approaches (Gersten et al., 2009; Institute of Education Sciences, 2017), but far less has been done to determine the optimal intervention dosage for a given individual, and what factors might account for individual differences in intervention-driven learning trajectories (Wanzek & Vaughn, 2010). The goal of the present study is to characterize intervention-driven growth trajectories over the course of an intensive (4 hours a day, 5 days a week) summer intervention program and examine individual-level characteristics that impact success. By studying response to intervention over the course of an intensive summer program, we can characterize intervention-driven learning trajectories without the confounding influence of concurrent educational activities.

What are the important components of a successful intervention?

Existing literature emphasizes the importance of phonological awareness instruction (Ehri, 1995; Slavin et al., 2010) and supplemental components of fluency and comprehension (Morris et al., 2012) in building a solid foundation for children with dyslexia. Neuroimaging studies further support the role of phonological processing deficits in dyslexia (Eden & Zeffiro, 1998; Hoeft et al., 2006, 2011; Kovelman et al., 2012; Saygin et al., 2013; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012) and have shown that successful intervention leads to changes in phonological processing circuits (Barquero, Davis, & Cutting, 2014; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009; Krafnick, Flowers, Napoliello, & Eden, 2011; Romeo et al., 2017; Temple et al., 2003). Research into the utility of phonological awareness-based interventions for struggling youth suggests that even the most severely disabled children will respond to directed instruction and that the earlier in a child's life you intervene, the more substantive and expeditious the outcomes for the average child (Berninger, 2001; Lovett et al., 2017; National Reading Panel, 2000; Snow, Burns, & Griffin, 1999). Further work supports the

importance of incorporating strategies for comprehension and fluent reading skill, on top of a foundation of phonological awareness (Morris et al., 2012; Stevens et al., 2016; Wolf & Katzir-Cohen, 2001). The success of these intervention approaches has led to policy initiatives aimed at creating nationwide standards for reading instruction and intervention (Committee on the Prevention of Reading Difficulties in Young Children, 1998; Gersten et al., 2009; National Reading Panel, 2000).

Ultimately, our goal is to teach children to fluidly and effortlessly read and comprehend text. Interventions that focus solely on phonological awareness have been successful in improving non-word reading skill and word-reading efficiency, but research has shown limited capacity for a pure phonics approach to generalize to fluency and comprehension skills (Lovett, Ransby, Hardwick, & Donaldson, 1989; Morris et al., 2012; Torgesen, 2000; Torgesen et al., 2001; Torgesen, Wagner, Rashotte, Alexander, & Conway, 1997). Hence, children show improved decoding skills but still struggle “reading to learn”. In an effort to increase generalizability of training, recent studies have explored the role of supplementary curricula, showing the positive influence of strategy-based techniques for word learning (Lovett et al., 2008), multi-component interventions targeting orthography, automaticity, and vocabulary (Morris et al., 2012), computer-based supplementary phonological awareness activities (Torgesen, Wagner, Rashotte, Herron, & Lindamood, 2010), morphology based learning (Nagy, Berninger, & Abbott, 2006), and elements of symbol imagery (Kosslyn, 1976; Linden & Wittrock, 1981; Sadoski, 1983). None of these studies aimed to find a single panacea; rather, each was designed to achieve a unified goal: discover “what works best in which programs for what students under which conditions” (Morris et al., 2012). However, while these studies reveal the efficacy of multi-componential interventions, they are unable to address the dose-response

relationship between the hours of training a child receives in one of the various curricula and that individual's response in terms of reading outcomes.

Is a reading intervention successful?

Studies of reading disability that use an intervention model have established a more robust understanding of dyslexia by developing a definition that not only characterizes the disorder, but also provides a blueprint for remediation (Berninger, 2001; Heim & Grande, 2012; Stanovich, 1996; Torgesen, 2006; Vellutino, Scanlon, & Reid Lyon, 2000) that is informed by a representative and diverse sample of struggling readers (Torgesen et al., 2001). For example, research on the impact of interventions across the socioeconomic continuum has found that intensive phonologically-based reading programs provide equitable outcomes across the board (Blachman, Tangel, Ball, Black, & McGraw, 1999; Lovett et al., 2008; Morris et al., 2012; Romeo et al., 2017). In accord with this perspective, the National Reading Panel concluded that phonics-based education represented the quintessential strategy, regardless of SES and pre-intervention reading ability (National Reading Panel, 2000).

The utility of a phonics-based intervention is clear at the group level, but the variety of outcomes seen in this corpus of research indicates that there are individual characteristics that determine how quickly a child responds. At the extreme end of the continuum, some studies have identified subsets of children who show limited improvements during an intervention (non-responders) (Al Otaiba & Fuchs, 2002; Torgesen, 2000; Torgesen et al., 1999). But in examining data from studies on children's response to intervention (RTI), it is also clear that some children show rapid gains within weeks of beginning an intervention, while others do not (Romeo et al., 2017; Vellutino et al., 2000). What characteristics differentiate non-responders from those showing the most substantial gains and, more generally, how might we predict at the

outset of an intervention whether it will be successful for a child? Or, more ideally, how might we align an intervention with a student's individual needs from the outset? Recent research has revealed the capacity of limited responders to improve with increased intervention intensity (Lam & McMaster, 2014; Sharon et al., 2009; Wanzek, J. ; Vaughn, 2007). Yet, this previous work does not predict or quantify the necessary intervention dosage that will produce measurable change in reading skill. Most research has focused on determining what interventions are effective at the group level and produce desirable results for the average child with dyslexia. But as it becomes clear that reading disability is heterogeneous (Joo, Donnelly, & Yeatman, 2017; Pennington, 2006), and that different individuals might learn better in different intervention programs, understanding these individual differences becomes an important research direction (Wanzek & Vaughn, 2010).

The present study

To date, the dominant model for studying intervention efficacy has been a pre-post design: children are tested before starting a program and after completing the program. The pre-post design has been used to determine not only those interventions that are more effective, but also has established foundational concepts about the mechanisms of dyslexia (Bradley & Bryant, 1983). However, this design precludes making inferences about the time-course of learning over the intervention and, with only two measurement points, individual growth estimates can be unreliable. Here we use dense longitudinal measurements over the course of an intensive intervention, combined with predictive measures for each child collected during a baseline period, to address four research questions: (1) What is the time course of learning for struggling readers enrolled in 8 weeks of intensive, individualized intervention? (2) Is intervention growth most parsimoniously characterized by a linear model, or are there diminishing/accelerating

returns with increasing hours of intervention? And (3) Can we predict who will benefit most from this particular program? We employ the Lindamood-Bell *Seeing Stars* intervention because it was designed to be employed in an intensive, one-on-one setting, over the course of the summer. Previous research has established the efficacy of this program (Krafnick et al., 2011; Romeo et al., 2017), and the goal of this work is not to compare the efficacy to other intervention approaches. Rather, we capitalize on the intensity of the program to model individual learning trajectories, characterize child-specific factors that predict success, and consider how growth modeling can inform intervention practice more generally. Specifically, we model the contribution of five predictor variables: IQ, phonological awareness, rapid naming, age, and initial reading ability (severity of impairment) to an individual's response to intervention.

Method

Participants

All parents of participants in the study provided written informed consent under a protocol that was approved by the UW Institutional Review Board and all procedures, including recruitment, child assent, and testing, were carried out under the stipulations of the UW Human Subjects Division. To ensure reproducibility of our findings, and to provide more detailed information on individual participant demographics, all the data and analysis code associated with this study is available in an online repository (https://github.com/yeatmanlab/Donnelly_2017). Recruitment was based on parent report of reading difficulties and/or a clinical diagnosis of dyslexia. We intentionally recruited a diverse sample of struggling readers in order to study variability in response-to-intervention. A total of 37 children were enrolled in the intervention study, all of which were native English speakers with normal or corrected-to-normal vision. 21 participants reported a clinical diagnosis of

dyslexia, and the other 16 participants reported struggles with reading but no formal diagnosis. Intervention participation occurred over the course of two summers (2016 and 2017), dividing the participants in two cohorts (Cohort 1 ($N = 26$), Cohort 2 ($N = 11$)). Those enrolled also had no history of neurological damage or psychiatric disorder. Of those enrolled, 31 participants completed the entire study protocol (five total sessions): two baseline sessions and participation in the full 160 hours of intervention (three additional sessions). Due to participant attrition, illness, unexpected family vacations and absences, and a scheduling issue, four participants received 120 hours, one received 152, one received 156, and another received 200 hours. Two participants only had 3 study visits (See **Method, “Statistics” for handling the case of missing data**). For the analysis of individual predictors, only those students who completed all four sessions spanning the intervention during the summer were included, giving a cohort of 31 students included in the analysis. Growth estimates are based on data from the full sample ($n = 37$) given that the statistical technique used accounts for missing data. The sample was balanced with 16 females (21 male), ranged in age from 7-13 ($M = 9.4$, $SD = 1.6$), and contained a heterogenous profile of reading ability centered 1.33 SD below the population average ($M = 80.1$, $SD = 13.7$), with IQ measures centered in the normal range ($M = 100$, $SD = 10.4$). This variety allowed us to investigate individual differences in response to intervention (RTI), and a formal diagnosis of dyslexia was not required for enrollment. Ten children matched on age ($M = 9.55$, $SD = 1.28$), reading ability ($M = 82.5$, $SD = 9.88$), and IQ ($M = 99.38$, $SD = 10.49$) were recruited to participate as a control group. The control group was used to model the effect of repeated testing and learning that would occur in a typical educational setting. Because our primary research questions focused on individual growth trajectories, and not on average intervention efficacy, we did not use random assignment to intervention and control conditions.

The control group underwent the same testing procedure, but did not participate in the intervention. For the control group, testing sessions occurred during a business-as-usual period, during which the children attended their usual academic classes.

Experimental Sessions

Each child participated in one baseline session three months prior to the beginning of the intervention program, a second baseline session immediately before starting the intervention, and three additional sessions to measure intervention-driven growth in reading skills. Except for the initial baseline session, each of the measurement sessions (including the second baseline) were spaced approximately 2.5 weeks apart over the course of the 8-week intervention, with midpoint measurements occurring during weeks 3 and 6. The second baseline session and the last measurement session immediately preceded/followed the intervention by, roughly, 2 weeks.

Each experimental session included a comprehensive assessment of reading related skills administered by researchers at the University of Washington who were not involved in the administration of the intervention program, and had no affiliation with Lindamood-Bell Learning Processes. The repeated battery for both baselines and the remaining visits included the Woodcock Johnson IV Test of Achievement (WJ) and the Test of Word Reading Efficiency-2 (TOWRE). From the WJ, the subtests administered were Letter-Word Identification (LWID), Word Attack (WA), Calculation (CALC), Oral Reading (OR), Sentence Reading Fluency (SRF), and Math Facts Fluency (MFF). These measures were combined to form the composite measures for Basic Reading Skills (BRS), Reading Fluency (RF), and Math Calculation Skills (MCS). From the TOWRE, the subtests administered were the tests of sight-word and phonemic decoding efficiency (SWE and PDE), which formed the TWRE Index composite score. During the first baseline, each child was also assessed for general cognitive abilities and phonological

awareness using the Weschler Abbreviated Scale of Intelligence - II (WASI, a composite of Vocabulary and Matrix Reasoning subtests) and the Comprehensive Test of Phonological Processing-2 (CTOPP).

Reading Intervention

Two cohorts of participants were enrolled in 160 hours of *Seeing Stars: Symbol Imagery for Fluency, Orthography, Sight Words, and Spelling* (Bell, 2007) over the course of 8 weeks of summer vacation. The first cohort was administered the intervention at three different *Lindamood-Bell Learning Centers* in the Seattle area in summer 2016, while the second cohort was administered the intervention at the Department of Speech & Hearing Sciences at the University of Washington. In both cohorts, the curriculum was administered by certified instructors from Lindamood-Bell. The *Seeing Stars* curriculum is a directed, individualized approach to training in phonological and orthographic processing skills. Employing a multi-sensory approach, the curriculum is incremental in training the foundations of literacy to systematically transition from letters and syllables, to words and connected texts. Reflective of its focus on imagery, the philosophy of *Seeing Stars* is that just as the constellations of the night sky are composed of stars, language is composed of many connected ideas and images. This concept of symbol imagery, with a well-documented research base (Kosslyn, 1976; Linden & Wittrock, 1981; Sadoski, 1983), is grounded in the idea that a robust understanding of letters and their associated sounds rests on the ability to recognize patterns and create mental representations at the level of the word. In a one-on-one setting with a certified instructor, children are encouraged to air-write the shape of letters and words, attend to their mouth movements, and visualize changes to words as the sounds are manipulated. In each lesson, an instructor will guide the student in a series of tasks that ask them to start with a word, visualize

its constituent letters, link their related sounds, and develop a multisensory framework for approaching printed text. *Seeing Stars* presents a confluence of orthography, imagery, and meaning in providing directed instruction that extends from decoding and spelling skills to fluency and comprehension. Additional information can be found in other publications that have assessed the efficacy of this intervention (Christodoulou et al., 2017; Krafnick et al., 2011).

Statistics

All data analysis was done using MATLAB® (The MathWorks, 2017). Linear mixed effects models were used to analyze longitudinal change in reading skill as a function of hours of intervention. Mixed effects models can accommodate missing data, and participants do not have to be dropped due to missing data points. To determine which variables should be modeled as random effects, we started with the most parsimonious model (hours of intervention as a fixed effect and participant as a random effect) and then used Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC) to compare models with different variables included as random effects. The models tested include:

(1) $score \sim time + (1|subj)$ a single random intercept that varies by participant

(2) $score \sim time + (1|subj) + (time - 1|subj)$ previous, with an independent random term for time grouped by participant

(3) $score \sim time + (1|subj) + (1|time)$ previous, with an additional random intercept that varies by time

(4) $score \sim time + (1 + time|subj)$ previous, with a random-effects term for the intercept and time

(5) $score \sim time + (time - 1|subj)$ previous, removing the intercept from the term added in model 4.

Following this approach for the each of the reading measures, we determined that the best fitting model included a subject specific intercept and an independent slope as random effects (2). To avoid over-fitting, we kept this same random effect structure and then added higher-order polynomial terms to the linear model to test for non-linear (quadratic or cubic) growth trajectories.

Results

Intervention drives growth of reading skills

Longitudinal measurements of reading skills were conducted for 37 children who participated in an intensive summer reading intervention program (Lindamood-Bell *Seeing Stars*, see **Method**). The intervention involved one-on-one instruction, four hours per day, five days per week, for eight weeks (160 hours total). The study involved 5 experimental sessions: 2.5 months prior to the beginning of the intervention ($SD = 1.03$ months), immediately before beginning intervention began, after 48.3 ($SD = 8.7$) hours of instruction, 102.2($SD = 12.7$) hours of instruction, and after completing the 160 hours of intervention. Age-normed, standardized measures of reading skills were stable during the baseline period before the beginning of the intervention, and then increased systematically through the course of the intervention (**Figure 1a**).

The stability during the baseline period indicates that growth during the intervention period reflected the effect of the training program, rather than the effect of repeated measures or the passage of time. Specifically, WJ Basic Reading Skills (BRS) and Reading Fluency (RF) measures were stable (BRS, $t(30) = -0.89$, $p = 0.38$; RF, $t(30) = 0.68$, $p = 0.50$), while standard scores on timed measures of decoding declined during the baseline period (TOWRE, $t(30) = -3.55$, $p = 0.001$). **Table 1** reports the mean test scores at each time point and the full dataset is available online (https://github.com/yeatmanlab/Donnelly_2017/blob/master/data).

Figure 1: Significant growth across reading measures. (A) Mean growth of composite reading skills. Growth curves, plotted using the intercept and slope estimates from a linear mixed-effects model with session as a categorical variable. The gray bar represents measurements during the baseline period. A flat, dashed line represents the population average (100) for reference. Results show growth across reading measures during the intervention period, and no change (or a decline) in scores during the baseline period. Error bars represent ± 1 SEM across participants. (B) Longitudinal growth of basic reading skills. Basic reading skills, measured by the Woodcock Johnson IV Basic Reading composite standard score, plotted for each individual child as a function of hours in the intervention. Participants completed up to 160 hours of intervention. The bold line

represents the linear fit based on a linear mixed-effects model ($p = 1.93 \times 10^{-14}$). (C)

Growth rates across reading measures. Bar heights depict growth in skills per hour of intervention estimated based on a linear mixed-effects model. Error bars depict standard errors from the linear mixed-effects model. Code and data to reproduce each figure is available in the online repository (e.g.,

https://github.com/yeatmanlab/Donnelly_2017/blob/master/figure1.m for code to

reproduce Figure 1). The tests abbreviated include the Woodcock-Johnson IV Tests of Achievement (WJ) Letter-Word Identification (WJ LWID), Word Attack (WJ WA), Basic Reading Skills composite (WJ BRS), Oral Reading (WJ OR), Sentence Reading Fluency (WJ SRF), Reading Fluency composite (WJ RF), Math Facts Fluency (WJ MFF), Calculation (WJ CALC), Math Calculation Skills composite (WJ MCS), Test of Word Reading Efficiency (TOWRE) Sight Word Efficiency (TOWRE SWE), Phonemic Decoding Efficiency (TOWRE PDE), and composite index (TWRE INDEX).

To compare the effects of the intensive intervention to changes that might be observed in a typical classroom setting (or due to repeated testing), we compared growth in the intervention participants to an age and reading skill matched control group that did not participate in the intervention. The control group did not show improvements in any of the age-normed composite reading measures across experimental sessions (**Supplementary Figures 1 and 2, Supplementary Table 1**), confirming that growth in reading scores is not due to repeated testing. Moreover, there was a significant group (intervention versus control) by time (days) interaction for all composite measures ($ps < 0.01$) confirming that the growth observed in the intervention group is significantly greater than the control group (see **Supplementary Table 1**).

To summarize growth for each measure, we fit a linear mixed effects model where changes in reading scores were modeled as a function of hours of intervention, with each

Table 1

Measures of reading growth during the intervention

	Intake Session		Session 1		Session 2		Session 3		Session 4		LME Linear Model	
Test Name	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Slope	P Value
LWID	76.80	16.33	75.32	16.53	79.03	14.97	84.14	15.02	86.34	13.88	0.07	6.49X10 ⁻¹⁰
WA	87.31	12.19	87.81	11.59	95.27	12.55	95.54	11.32	101.86	12.30	0.09	3.44X10 ⁻¹⁸
BRS	80.63	13.80	80.08	13.67	84.68	13.01	88.68	12.62	91.23	13.74	0.07	1.93X10 ⁻¹⁴
OR	78.23	15.89	78.24	16.48	79.72	14.57	84.05	13.54	87.80	11.95	0.06	1.68X10 ⁻¹¹
SRF	72.54	16.93	74.59	17.57	73.89	16.59	76.70	16.40	77.63	15.92	0.03	1.10X10 ⁻⁴
RF	71.71	17.52	73.03	18.15	73.81	16.22	76.78	16.44	79.00	15.48	0.05	4.65X10 ⁻⁰⁸
SWE	74.23	13.63	73.24	14.91	73.24	15.72	75.51	14.91	76.74	16.79	0.02	1.09X10 ⁻³
PDE	76.91	10.85	73.43	11.68	80.24	11.40	80.14	10.94	82.23	11.56	0.05	1.69X10 ⁻¹⁰
TWRE	74.40	11.93	72.05	12.99	75.46	13.16	76.59	12.44	78.43	13.88	0.04	2.03X10 ⁻⁰⁸
MFF	85.45	16.55	84.03	17.13	80.09	16.44	76.84	17.67	80.06	16.21	-0.03	5.85X10 ⁻⁴
CALC	--	--	85.73	13.35	83.97	12.70	83.97	14.10	82.81	13.20	-0.02	0.086
MCS	--	--	84.10	14.73	80.77	13.96	78.81	14.65	81.06	12.57	-0.02	0.024

Note. Reading battery results across the four experimental sessions and initial intake session related to participation in 160 hours of directed reading intervention through the *Seeing Stars* curriculum of *Lindamood-Bell Learning Processes*. Means and standard deviations (SD) are shown as well as the model statistics from the linear mixed effects model analysis. The model analysis includes the group slope estimate for rate of change in RTI (Slope) and significance value (P Value). Reading battery consists of the Woodcock-Johnson IV Letter-Word Identification (LWID), Word Attack (WA), Basic Reading Skills (BRS), Oral Reading (OR), Sentence Reading Fluency (SRF), Reading Fluency (RF), Math Facts Fluency (MFF), Calculation (CALC), and Math Calculation

Skills (MCS); Test of Word Reading Efficiency 2 Sight Word Efficiency (SWE), Phonemic Decoding Efficiency (PDE), and the TWRE Reading Index (TWRE). All scores presented are standardized measures.

individual's slope and intercept included as independent random effects within the model (**See Method, "Statistics"**). **Figure 1b** shows growth trajectories for each individual subject: Even though there was substantial variability in initial reading scores, there was steady growth during the intervention. All measures of reading skills showed significant intervention-driven growth (**Figure 1c**). Using a mixed effects model to compare growth rates between the binned timed and untimed reading measures we found that untimed measures (Woodcock Johnson IV, Word Attack (WA), Letter-Word Identification (LWID)) showed more rapid growth than timed measures (TOWRE, Sight Word Efficiency (SWE), Phonemic Decoding Efficiency (PDE)) ($\beta = 1.98$, $t(146) = 5.70$, $p = 6.34 \times 10^{-8}$). The untimed measure of pseudo word decoding (WA) showed the greatest rate of growth. This pattern was paralleled for measures of reading fluency, with the untimed task (OR) improving more than the timed comprehension task (SRF).

To control for familiarity with testing, and examine whether learning generalizes to other academic skills, we also collected measures of mathematical skill. We found that Woodcock Johnson Math Facts Fluency (MFF), a timed measure of arithmetic skill, and Calculation (CALC), an untimed measure of quantitative skill, were stable over the intervention (**Figure 1c, Table 1**). These results indicate that students' growth in reading skills were due to the specific training program rather than due to the Hawthorne effect (Cook, 1962), where scores increase due to repeated testing. Table 1 details the results of the linear mixed-effects modeling analysis for each of the reading-related behavioral measures.

Growth in reading skills is not significantly different than linear

In our sample, 160 hours of *Seeing Stars* produces, on average a 0.7 SD increase in word reading scores (**Table 1**); however, this growth could occur during the first few weeks of intervention with reading skills remaining roughly constant after the beginning of the program.

Alternatively, many hours of training may be required to see any change in scores. Lastly, each hour of intervention could produce an incremental improvement in reading skill.

To better illustrate the various trajectories that our data could reveal, **Figure 2** shows the change in Basic Reading Skills Composite Score we observed from first visit to last. A pre-post design makes it possible to determine the average amount of change in a score, but does not provide any information about how participants got from point A to point B. The different curves, illustrate these various possibilities. The dotted curve demonstrates a rapid initial response which saturates towards the end of the intervention. This growth curve would imply that there are diminishing returns for a longer intervention and could be detected based on a significant negative quadratic effect in the model. The dashed curve demonstrates slow initial response with an accelerating rate of growth after more hours of intervention. This growth curve would imply that a longer intervention is required to realize the benefits of the curriculum and could be detected based on a significant positive quadratic effect in the model. Finally, the solid curve demonstrates a constant linear rate of change from start to finish. This growth trajectory would imply that each hour of intervention provides a subsequent unit growth in reading skill. These three dose-response curves achieve the same end result, but have vastly different implications for how we might optimize intervention practice.

Figure 2: Hypothetical growth trajectories. When reading skills are measured at multiple time-points over the course of an intervention, we might observe different patterns of growth. In the dotted curve, rapid initial growth levels off over time, which would be detected as a significant negative quadratic effect. In the dashed curve, slow initial growth speeds up over time, which would be detected as a significant positive quadratic effect. The solid line shows linear growth.

To detect potential non-linearities in the dose-response relationship between hours of intervention and reading growth, we added higher order polynomial terms (quadratic and cubic) to the mixed effects model. These models included the same random effects structure (see **Method**) to avoid over-fitting the model. We used Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC) to compare the goodness-of-fit for models that include (a) only a linear term, (b) linear and quadratic terms, and (c) linear quadratic and cubic terms, and to determine if more complex models, with non-linear growth rates, were a better fit to the data than the more parsimonious linear model.

Our results indicate that the more complex models are not a significantly better fit to the data than the linear model. **Figure 3** shows the coefficients for the quadratic and cubic terms; no

reading measure showed significant quadratic or cubic effects. Hence, we conclude that over 160 hours of intervention, improvements in reading skills follow a predominantly linear trajectory.

The finding that growth is linear draws attention to the issue of extrapolation from our data range. We can assume that linear growth would not persist indefinitely and that at some intervention dosage participants will stop benefiting from more hours of intervention. Dose-response curves typically follow a sigmoidal shape (depicted in **Figure 3c**), where small dosages provide limited returns, but as the dosage increases, the effect grows until the curve saturates indicating that added dosage provides limited returns. Our results indicate that our intervention window (160 hours) fell in this intermediate range of the curve, where growth is roughly linear (Grayed out section of Figure 3c) due to the lack of significance when higher-order variables are introduced into the model fit. Future research will be needed to determine the minimum hours needed to produce an improvement and the saturation point of the curve.

Figure 3: Comparison of non-linear models of reading growth trajectories. Coefficients for the quadratic (a) and cubic (b) effects with error bars representing ± 1 SEM across participants. These effects were not significant for any of the reading measures, confirming that growth is predominantly linear. Panel c shows a typical dose-response

curve. Our findings of linear growth in reading skills, without any significant deviations from linearity, indicate that 160 hours of *Seeing Stars* lives in the shaded gray area of the dose response curve.

Individual differences in reading growth rate are associated with IQ and reading skill prior to intervention

Previous work has demonstrated the components of a successful dyslexia intervention program; however, there is substantial variability in how any given child will respond to the intervention. For example, as shown in Figure 1b, some children demonstrated up to 2SD improvement in reading skills while other children showed more limited growth. To investigate individual differences in children's response-to-intervention (RTI), we performed a correlational analysis of individual growth rates, using a linear fit to each participant's intervention sessions, with five predictor variables: an intelligence composite (IQ) of vocabulary (Vocab) and matrix reasoning (MR), phonological awareness (measured with the CTOPP Elision subtest), rapid naming, age, and initial reading ability (severity of impairment) (**Figure 4**).

Figure 4: Predicting Individual growth. Individual differences in response to intervention were analyzed using a correlation analysis between slope estimates from the linear mixed effects model and the following predictor variables: IQ, Initial reading ability, and the IQ-reading discrepancy. From these analyses, there is a statistically significant negative association between initial reading ability and growth for the composites for Basic Reading Skill (BRS) and Reading Fluency (RF), between IQ and growth for all composite measures but a non-significant correlation for other predictors of TOWRE growth and the discrepancy factor. These findings indicate strong response for children of lower IQ and lower initial reading ability, with non-significant impact of their discrepancy.

These analyses reveal a significant correlation between composite IQ on intervention-driven growth of basic reading skills (BRS, $r = -0.39$, $p = 0.03$), reading fluency (RF, $r = -0.56$, $p = 0.001$), and word reading efficiency (TOWRE, $r = -0.48$, $p = 0.01$). Additionally, children's initial reading ability was negatively associated with growth of basic reading (BRS, $r = -0.39$, $p = 0.03$) and fluency (RF, $r = -0.51$, $p = 0.004$). In other words, children with lower IQ, and lower initial reading scores benefited the most from the intervention (**Figure 5**). Phonological awareness scores did not predict children's RTI in terms of any outcome measure (BRS, $r(31) = -0.05$, $p = 0.80$, RF, $r(31) = -0.04$, $p = 0.81$; TWRE, $r(31) = -0.02$, $p = 0.93$). Rapid naming, measured with the CTOPP Rapid Naming composite measure, was also not predictive, (BRS, $r(31) = -0.20$, $p = 0.28$; RF, $r(31) = -0.01$, $p = 0.95$; TWRE, $r(31) = -0.02$, $p = 0.89$). Age, at the start of intervention, also lacked significant predictive value (BRS, $r(31) = 0.01$, $p = 0.94$; RF, $r(31) = 0.12$, $p = 0.52$; TWRE, $r(31) = 0.05$, $p = 0.78$). Only IQ predicted growth in TOWRE scores ($r = -0.48$, $p = 0.01$).

Figure 5: Median-split growth trajectories. To explore the impact of initial reading ability on growth trajectories, change in reading ability (WJ Basic Reading Skills) across the intervention period (sessions 1 to 4) was split along the median (WJ BRS = 82) of initial reading ability. These results show that more struggling readers (solid) demonstrate more expeditious growth than their less impaired peers (dashed).

Historically, the dyslexia literature has made a distinction between IQ-discrepant poor readers (reading scores are lower than IQ score) and IQ-consistent poor readers (reading scores and IQ scores are both below age-based norms) (Rutter & Yule, 1975), because an IQ-reading score discrepancy was required for the provision of special education services (Stuebing et al., 2002; Vellutino et al., 2000). However, the utility of this measure has been questioned because there is little evidence that an IQ-reading discrepancy is relevant for decisions about treatment (Berninger, 2001; Francis, Shaywitz, Stuebing, Shaywitz, & Fletcher, 1996; Siegel, 1989; Stuebing et al., 2002). We therefore calculated IQ-reading discrepancy scores as the difference between baseline IQ and baseline Basic Reading Scores for each subject, and then tested whether IQ-reading discrepancy scores were predictive of a child's RTI. We found no significant correlation with any measure of intervention success, in line with previous studies arguing that this discrepancy measure is not useful in determining who should receive treatment (Ferrer, Shaywitz, Holahan, Marchione, & Shaywitz, 2010; Francis et al., 1996; Schatschneider, Wagner, & Crawford, 2008; Stanovich, 1996; Stuebing et al., 2002; Tanaka et al., 2011; Vellutino et al., 2000). Our results support research by Vellutino and colleagues, showing that the severity of reading impairment in relation to IQ is uninformative about a student's responsiveness to intervention.

One reason that the IQ-reading discrepancy might be uninformative is that low IQ might stem from a lack of reading experience. For example, studies have shown that vocabulary size is intimately tied to reading experience (Berninger, 2001; Vellutino et al., 2000). Our data supports this assertion; initial IQ and initial reading scores are themselves correlated ($r = 0.38, p = 0.03$) and, on their own, each measure predicts children's improvement in BRS (**Figure 4**; IQ $r(31) = -0.39, p = 0.03$; initial reading $r(31) = -0.39, p = 0.03$). To piece apart the relationship between IQ and initial reading ability in determining success, we used a multivariate regression model to control for the correlation between the two predictors and also pull apart the independent influences of the verbal and non-verbal components of the IQ composite: vocabulary (Vocab) and matrix reasoning (MR). When BRS, Vocab, and MR are all entered as predictors into the model, we find that each predictor is influential in different reading skill sets. In predicting BRS growth, MR shows a significant effect when controlling for the effect of initial reading and Vocab ($\beta = -0.16, t(29) = -2.20, p = 0.04$). For RF growth, initial reading is the solely influential predictor ($\beta = -0.06, t(29) = -2.27, p = 0.03$). Finally, for TWRE growth, Vocab proves to explain the majority of the variance ($\beta = -0.09, t(29) = 2.15, p = 0.04$). The reading-IQ discrepancy proves uninformative, yet each component represents a significant predictor in its own domain.

Discussion

Enrollment in 160 hours of directed, one-on-one intervention over the course of a summer led to systematic growth in reading skills, including real and pseudo-word decoding, reading fluency, and comprehension. This contrasted with stability or decline seen during a pre-intervention baseline period, and lack of change seen in a group of age- and reading skill-matched control participants. Importantly, reading skills increased linearly with each hour of

intervention, carrying practical implications for decision making around intervention policy and practice. However, the amount of improvement (linear growth rate) varied among participants, with analyses revealing an inverse relationship between an individual's growth in reading skill and both composite IQ and baseline reading ability. In aggregate, these analyses demonstrate the success of this summer intervention program, particularly for the most struggling readers in our sample. However, since we have not directly compared this specific intervention approach against other approaches, we cannot infer which specific factors in the intervention program were most important for success (e.g., one-on-one training versus the specific curriculum).

The results of this intervention study support the stance that viewing a child's reading disability in the context of their comparative IQ does not provide insight into their propensity for remediation (Al Otaiba & Fuchs, 2002; Vellutino et al., 2000). The importance of an IQ-reading score discrepancy for defining dyslexia (Rutter & Yule, 1975) has been consistently refuted in the literature (Berninger, 2001; Ferrer et al., 2010; Fletcher et al., 1994; Schatschneider et al., 2008; Siegel, 1989; Stanovich, 1996; Stuebing et al., 2002; Vellutino et al., 2000), leading to revised legislation (Individuals with Disabilities Education Act (2015)). We provide further evidence that this discrepancy does not provide useful prognostic information for intervention outcomes. In fact, the evidence that our lower IQ participants responded more efficiently to intervention, regardless of their IQ-reading discrepancy, supports the important distinction between IQ and reading ability in the characterization of dyslexia (Stanovich, 1996). The more limited growth seen in the higher IQ students may be related to previous instruction and intervention, reflecting the complexity added by the interaction between a child's history of reading instruction and their degree of disability (Torgesen, 2006). In sum, these results show no meaningful difference between discrepant and non-discrepant children in their response to

intervention and support the breadth of research criticizing the use of the IQ-reading discrepancy factor as grounded in a “wait to fail” model (Schatschneider et al., 2008).

The result that children with initially greater impairments developed their reading skills more quickly highlights the tendency for certain individuals to be more readily-remediated (Vellutino et al., 2000). Since there was a positive correlation between composite IQ and initial reading ability, we cannot treat these as independent factors: The use of the intelligence measures in the classification of dyslexia is tenuous due to the tremendous impact the inability to read can have on test performance (Stage, Abbott, Jenkins, & Berninger, 2003; Vellutino et al., 2000). Because reading and IQ measures are both influenced by reading experience and language exposure, these two measures provided redundant information and, thus, IQ scores are a biased measure of intellectual ability in reading impaired children (Vellutino et al., 2000). Consistent with research by Torgesen and colleagues on the utility of IQ in learning disabilities research, our results demonstrate that the collection of IQ measures is influential in describing the role of aptitude in reading education. The relative success of more impaired readers, illustrated in **Figure 5**, suggests that initial severity of disability, which is, itself, perhaps tied to previous reading instruction and experience, strongly predicts response to intervention.

Unique to this intervention study is the intensity of instruction: 160 hours of instruction over an 8-week period. To our knowledge this intensity is unmatched (for review of intervention studies see (Al Otaiba & Fuchs, 2002; Wanzek et al., 2013), and provides a strong paradigm to characterize growth and response to intervention. In the context of intervention research that gained traction in the 1990s, the recommended dosage has been determined by logistical feasibility, coherence with ongoing schooling, and motivated by the goal of enhancing decoding skill with the hope that improved decoding will extend to fluency and comprehension (Lyon &

Moats, 1997). As an individual child's response is so variable, there is no golden-rule for intervention dosage (B. A. Shaywitz & Shaywitz, 1994); rather, the onus on educators is to discover the appropriate dosage that gives the struggling reader the necessary decoding foundation to, theoretically, jumpstart their ability to catch up to their peers in the realm of fluent comprehension (Lyon & Moats, 1997; Torgesen, 2006; Vadasy, Sanders, & Abbott, 2008). Here we find significant growth in both decoding skill and reading fluency, and provide data demonstrating how much improvement we can expect based on each hour of one-on-one intervention.

The predominant method for studying intervention efficacy is a pre-post design, where a single measurement before and a single measurement after intervention are used to determine the amount of change in reading skills. This method has been extremely effective in answering the question of whether a given intervention program is effective in improving reading skill during the treatment period, and comparing the efficacy of different intervention approaches. Some questions that remain unanswered by this design concern the dose-response relationship between the amount of intervention and growth in reading skills. By conducting multiple experimental sessions over the course of the intervention we can answer important questions related to intervention "*dosage*": How much intervention is appropriate for a child? How much is too little? What is the most cost-effective way to achieve the greatest gains? Is this intervention worth the investment, and what should be the recommended dose, for a given child? And what individual, student-level factors are associated with success? However, it is also important to keep in mind that we characterized the dose-response curves for one specific intervention program, and with a relatively small sample of subjects. Therefore it will be important to extend this methodology to more diverse samples and other intervention programs.

Our study, like others that have applied growth curve analyses (Lovett et al., 1994; Lyon & Moats, 1997; Skibbe, Grimm, Bowles, & Morrison, 2012; Stage et al., 2003; Torgesen et al., 1999, 2001; Vadasy et al., 2008), represents an effort to create a systematic method for determining the optimal intervention dosage that can inform how families and school districts allocate resources to support struggling readers. By looking at growth as a function of the hours and type of intervention, models of individual growth curves provide a tool for making cost-effective, evidence-based decisions about remediation. As the benefits of phonologically-based intervention saturate (Lyon & Moats, 1997), the challenge of continued intervention is to generalize this growth to gains in fluency and comprehension (Lovett et al., 1994; Skibbe et al., 2012; Torgesen, 2006). Based on longitudinal measurements, researchers and educators alike can monitor the gains across reading-related skills to determine for each individual child the type and dosage that maximizes return on investment. With this information, parents and educators can weigh the costs and benefits to make informed decisions about their child's learning. Likewise, school districts and policymakers can use such information to save resources in providing requisite accommodations.

Unlike previous intervention research, the current study does not seek to determine the efficacy of a particular program; rather, we aim to use intervention as a means to illustrate the time course of learning, lending to the ability of future research to identify the hallmarks that define an effective, gold-standard model for the individualized intervention of struggling readers. Although the approach used in this study provides information that is useful for policy around cost-effective, evidence-based intervention, these results alone provide limited answers and present additional questions. For example, the *Seeing Stars* program is a multi-componential intervention, which presents challenges to studying the discrete benefits of any specific

technique. Additionally, the use of more comprehensive questionnaires exploring the educational history of participants could provide useful information regarding the effect of experience on response to intervention. Finally, long-term follow up measurements are critical for determining the ability of any given short-term intervention program to provide enduring benefits for struggling readers. Reading research should continue to strive for models that consider a child's unique intellectual profile and educational experience to optimize the intervention strategy for long-term success.

Acknowledgments

We would like to thank the past and present members of the Brain Development & Education Lab: Sung Jun Joo, Emily Kubota, Altaire Anderson, and Douglas Strodtman for their contributions to the planning and execution of the study, Maryanne Wolf and Diane Kendall for their advice on study design and interpretation, and Lindamood-Bell Learning Processes for providing participants in the study instruction free-of-charge. This work was funded by the National Science Foundation, Division of Behavioral and Cognitive Sciences Grant 1551330 to J.D.Y.

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Supplementary Items

Supplementary Figure 1: Control group comparison. This figure is identical in analysis to Figure 1a, for the cohort of 10 age and reading ability matched control participants. Each point represents the model fit curve using the linear effects model across control period sessions that mimicked the intervention group. Results show that the control participants experienced no significant growth of composite measures in response to participation as controls over the same time period of observation.

Supplementary Figure 2: Growth statistics from linear mixed effects model. This figure is identical to Figure 1c in its analysis of the growth statistics from the linear mixed effects model, but for the cohort of 10 age- and reading ability-matched control participants. Results show that, with the exception of limited growth of WJ Oral Reading (OR) and TOWRE Phonemic Decoding Efficiency (PDE), no measure demonstrated significant change, with growth trends in varied directions. Significant growth in OR and significant decline in PDE, in conjunction with non-significant trends in other measures, demonstrates inconsistent change in comparison to intervention cohort. Growth estimate axis is scaled in terms of standard score increase per unit day of control condition.

Supplementary Table 1

Measures of reading skill for the matched control group

Test Name	Intake Session		Session 1		Session 2		Session 3		Session 4		LME Linear Model		LME Interaction Model	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Slope	P Value	Coefficient	P Value
LWID	79.10	10.47	79.20	12.63	85.20	10.70	77.17	7.83	81.40	10.53	0.18	0.17	0.14	0.01
WA	92.60	12.53	90.70	11.67	93.10	8.61	90.17	4.49	89.60	12.28	-0.18	0.31	0.19	0.00
BRS	84.20	10.12	82.50	9.88	88.00	8.42	82.00	5.33	86.00	12.25	0.03	0.79	0.12	0.01
OR	82.50	10.63	84.30	5.10	85.60	8.58	85.50	6.47	85.00	10.12	0.27	0.03	0.14	0.00
SRF	79.90	9.77	79.40	11.41	78.60	11.15	81.50	15.64	81.60	14.76	-0.08	0.57	0.06	0.12
RF	78.70	8.93	79.10	9.76	78.90	10.75	81.17	13.20	80.40	14.29	0.04	0.67	0.09	0.01
SWE	74.60	13.10	73.80	13.75	74.10	14.82	74.83	14.18	77.40	17.60	-0.08	0.45	0.04	0.23
PDE	80.60	8.71	78.80	9.96	78.10	6.66	81.33	9.50	77.60	9.53	-0.27	0.02	0.14	0.00
TWRE	76.60	10.48	75.00	11.14	75.00	10.39	77.00	12.31	76.20	13.75	-0.17	0.07	0.09	0.00

Note. Reading battery results across the four experimental sessions and initial intake session related to participation as a matched control. Descriptive measures including mean and standard deviation (SD) are shown as well as the model statistics from the linear mixed effects model analysis. The model analysis includes the group slope estimate for rate of change in RTI (Slope) and significance value (P Value). The interaction model analysis included all participants and lists the beta value (Coefficient) and significance (P Value) of the effect of Time (days) X Group (Intervention (N=37) or Control (N=10)). Non-significant interaction coefficients seen in the SRF and SWE measures reveals high variability and added noise in the control group as a result of small sample size. Reading battery consists of the Woodcock-Johnson IV Tests of Achievement Letter-Word Identification (LWID), Word Attack (WA), Basic Reading Skills Composite (BRS), Oral Reading (OR), Sentence Reading Fluency (SRF), Reading Fluency Composite (RF), Math

Facts Fluency (MFF), Calculation (CALC), and Math Calculation Skills Composite (MCS); Test of Word Reading Efficiency 2 Sight Word Efficiency (SWE), Phonemic Decoding Efficiency (PDE), and the TWRE Reading Index Composite (TWRE).