Title: Reading Fluency Matters: NIH R21 HD090460-01A1

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Preface: This document contains the text of an unfunded R21 grant proposal submitted to the US National Institutes of Health on November 16, 2016 (NIH Identifier: HD090460-01A1). This is the third version of the proposal. The previous two having been submitted on February 16, 2016 (NIH Identifier: D090460-01A0) and October 16, 2014 (NIH Identifier: HD085131-01A0), the latter under a different title. None of these was funded. Appended to the end of this document, are the study section roster (LCOM) and reviews for the present (Nov. 2016) version of the proposal.

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Fluency is an essential feature of skilled reading. Reading speed is an overt reflection of automaticity in decoding and similarly deft control over other component skills. There is considerable support for oral reading speed as a valid and reliable indicator of general reading skill. In fluent reading, whether oral or silent, processes of word recognition, comprehension, and eye movement control must be tightly coordinated, as characterized in several implemented models of eye movements over print (Reichle et al., 2013; Reilly & Radach, 2006; Engbert et al., 2005). Oral reading, in addition to those requirements shared with silent reading, places an additional demand on the reader: the need to produce accurate, prosodically appropriate speech in conjunction with the reading process itself. Both oral and silent reading rely not only on good control of component processes, but also on facile coordination of those processes (Berninger et al., 2001; Breznitz, 2003). Rapid automatized naming (RAN) is another fluency-like predictor of reading skills (see Bowey, 2005; Kirby et al., 2010; Hulme & Snowling, 2012; Cutting & Scarborough, 2006; Wolf et al., 2000). RAN's task demands overlap considerably with reading, especially oral reading (Denckla & Rudel, 1974). Yet, the nature of the connections between the two capabilities remains uncertain. This research exploits commonalities between reading and RAN to help resolve uncertainties in their causes. We do so by working toward a unified, theoretical account of performance across tasks. Our main purpose is not to explain RAN as such, but a model of reading fluency that explicitly handles RAN will have distinct advantages over one that does not. It will be constrained by the need to accommodate both tasks, and so may provide insight into relationships between the two that will prove helpful in refining practical uses of RAN as a reading assessment. Our approach is two-fold. First, we will assess relationships among oral and silent reading, and standard indicators of reading skill in three critical periods in the development of skilled reading: a learning-to-read group (7-8yo), a transition-to-fluency group (10-11yo), and a full-literacy group (17-18yo). We will evaluate developmental differences between groups and individual differences within groups. We will apply new ways to investigate RAN performance and oral and silent reading fluency derived from analysis of gaze behavior, and of asynchronies in gaze and speech behaviors produced during these tasks (Jones et al., 2008). We make novel use of speech processing technology to facilitate alignment of speech and gaze signals to accommodate the large volume of speech data generated by the project. Second, we will implement a unified model of coordination among component processes for oral and silent reading (Reichle et al., 2009; Reichle, Pollatsek, et al., 2012). A successful unified model will serve as a testbed for investigating structural relationships among oral and silent reading, RAN and component skills.

SPECIFIC AIMS

Fluency is a cornerstone of skilled reading. Oral reading speed is an indicator of automaticity in decoding and deft control over other component skills. Further, although silent reading is a more natural mode for the mature reader, there is considerable support for oral reading speed as a valid and reliable indicator of general reading skill (Deno et al., 1982; Fuchs et al., 1988; Silverman et al., 2013). So, fluency is a reflection of the constellation of processes that underpin fast efficient reading, whether oral or silent, and their interactions. In fluent reading of either modality, processes of word recognition, parsing, semantic integration, and eye-movement control must be tightly coordinated.

Efficient reading, regardless of modality, relies not only on good control of its component processes, but also on facile *coordination* of those processes, as characterized in several implemented models of eye-movements over print (Engbert et al., 2005; Reichle et al., 2013; Reilly & Radach, 2006). All of these models highlight word properties (familiarity, predictability, etc.) as important factors in regulating the eye's progress through a text, due to their influence on word identification. They are all similarly limited insofar as their foci are restricted to silent reading. Skilled oral reading places demands on the reader beyond those of silent reading: the need to produce accurate, prosodically appropriate speech. And so a theoretical account of oral reading fluency should accommodate silent reading efficiency as a sub-case. Further, rapid automatized naming (RAN) shares significant task demands with reading, especially oral reading, although requirements for item identification and meaning composition are reduced or eliminated (Berninger et al., 2001; Breznitz, 2003; Denckla & Rudel, 1974). Our research addresses the challenges of identifying connections between components of fluent reading across modalities. This project will provide for improved, model driven, understanding of structural connections among oral and silent reading and RAN performance.

Our approach is two-fold. First, we will assess relationships among oral and silent reading, RAN and standard indicators of reading skill in three developmental periods of special significance to literacy acquisition: a learning-to-read group (7-8yo), a transition to fluency group (10-11yo) and a full-literacy group (17-18yo), allowing us to evaluate experience related differences within and between groups. In that connection we will apply new ways to investigate oral and silent reading fluency derived from analysis of asynchronies in gaze and speech behaviors produced during these tasks (Jones et al., 2008). Another set of predictions is that increasing fluency, both within and across groups, will correlate with increases in the effect of context on both gaze time and speaking time. This should surface in the data as longer-range correlations within the time series for gaze and speech. We will use the method of fractal analysis to evaluate specific hypotheses regarding serial correlation structure of time series for gaze and speech (Diniz et al., 2011). An additional methodological innovation of this research is to use speech processing technology to facilitate alignment of speech and gaze signals, necessary to accommodate the large volume of speech data generated by the project.

Second, we will implement new (extended) models of coordination among component processes to accommodate silent reading, oral reading and RAN performance, within a unified framework (Reichle et al., 2012a; Reichle et al., 2009). The key difference between these new extensions and existing frameworks for understanding silent reading behavior is that the former will incorporate parameters for speech motor programming and speech production. This unifying model will afford a testbed for investigating structural relationships among oral and silent reading fluency and their component skills (Perfetti, 1985; Reichle et al., 2013; Schwanenflugel et al., 2004). Although RAN is not our primary focus, a model of reading fluency that explicitly incorporates RAN has advantages over one that does not. Constrained by the requirement to accommodate both reading and RAN, it may provide insight into the relationship between RAN and reading that will prove helpful in refining practical uses of RAN as an assessment. Final models, tuned to human data collected for this project, will serve as an explicit theory of coordination among cognitive components that support oral and silent reading fluency and RAN performance, and developmental changes therein.

The proposed research will yield knowledge for improved understanding of subprocesses central to development of fluent reading and coordination among them. In working toward this goal, we draw on the substantial experience of our team in the cognitive bases of reading skill and in the technical domains of speech analysis, eye-tracking, and cognitive model building. In this study of connections among RAN, reading fluency and reading skill, our **Specific Aims** are:

1. To assess relations between oral and silent reading at three stages of development using standard indicators of gaze behavior and conventional measures of component reading skills.
2. To implement a computational model sufficient to account for relations between oral and silent reading fluency which will provide improved understanding of these tasks and the structural relations between them for readers three at stages of development.

A. SIGNIFICANCE

Too little is known about the factors that facilitate or retard progress from basic to advanced reading skill. Achievement of fluency is a crucial milestone along that path, after decoding accuracy is attained. A theoretical understanding of fluency has been hampered by the lack of models detailing relationships among the interacting processes that contribute to fluency. We adopt the E-Z Reader (EZR) theoretical framework for reasoning about relationships between cognition and gaze behavior. We extend the framework to accommodate oral reading and RAN. These, together with an existing EZR model of silent reading, will provide an explicit testbed to be used to refine our understanding of the intersecting and unique demands of silent and oral reading and RAN. Our models are informed by and vetted against human reading and RAN data, gathered for the purpose. We will incorporate into the models the empirical relationships among oral and silent reading, RAN performance and indicators of reading skill at three developmental stages: beginning readers, who grapple with the mechanics of word reading; transitional readers, in the early stages of reading for content; and more experienced individuals, as they approach full mastery of reading (§C3.1).

Current models of eye movements over print, including E-Z Reader, are limited in their capacity to explain connections between oral and silent reading fluency and general reading skill, for two reasons. One factor is that standard EZR and similar models lack accommodation for the speech production component of oral reading. The standard EZR model accommodates *silent reading only*, although some recent work motivates extensions to non-reading visual search tasks (Reichle et al., 2012a; Reichle et al., 2012b). Our new EZR variant for oral reading adds a mechanism for modeling the interplay of speech motor requirements of oral reading (and RAN) with oculo-motor control, lexical access, and lexical integration (the latter three components are already part of the standard model; see §C2.3). A second limitation of conventional EZR is its focus on *lexical* properties (e.g., word frequency and predictability) as primary regulators of the eye's path through a text (Engbert et al., 2005; Reichle et al., 2013; Reilly & Radach, 2006). While RAN shares some task demands with reading, especially oral reading, it minimizes the load on processes responsible for item identification and meaning composition, relative to oral or silent reading. Our proposed new EZR variants for RAN and oral reading, together with the standard EZR model, form a highly constrained architecture that can be considered an explicit theory of the connections between reading fluency across modalities, and RAN performance. So, this extension of an existing framework for modeling gaze control will provide our project and the field of reading research with new tools for understanding associations among two modes of reading and RAN performance.

Our project will also refine a new methodological approach to the analysis of asynchronies in the time course of linked speech and gaze data generated in RAN and oral reading fluency tasks. Specifically, we borrow the technique of *forced alignment* (FA) from the field of automated speech recognition to parse recorded speech into words. Application of FA makes the analysis of speech data tractable on the scale proposed in this application. Continued refinement of this methodological innovation as part of the proposed research will provide the field with a new tool for the investigation of reading fluency.

B. INNOVATION

First, we will evaluate specific hypotheses about the nature of oral and silent reading fluency through use of time-locked speech and gaze data, together with psychometrically sound measures of reading-related skills, from children at three stages of reading skill. Second, we will extend the EZR model of silent reading to provide a mechanistic account of interactions among processes for lexical access and integration, oculo-motor control and speech-motor control. In doing so we will create an adaptation of the basic EZR model to accommodate oral reading and its connection with silent reading. An explanation for RAN performance is expected to emerge naturally from this extended model. Parallel models will be used to refine our understanding of fluency in oral and silent reading, for nomothetic performance at three stages of reading skill development. Models will help to clarify the overlapping and unique requirements of each task, which may differ across developmental epochs. A third, methodological, innovation is the refinement of techniques for annotating large scale time-locked speech and gaze signals. Use of forced alignment mitigates a significant practical obstacle: the labor intensive nature of segmenting speech files for further analysis.

C. APPROACH

C1. Background

C1.1 Conceptual Background

Automaticity in word recognition is crucial to skilled reading (Perfetti, 1985), but it is not the endpoint. Processes underlying oral reading fluency have been shown to play either a direct or mediating role in reading comprehension (e.g., Macaruso & Shankweiler, 2010; Silverman et al., 2013; Tilstra et al., 2009). Models of eye movements in reading do highlight word characteristics as important factors in regulating the eye's progress through a text, but equally important is the coordination lexical access, lexical integration, oculo-motor control and, in the case of oral reading, speech motor-control (Engbert et al., 2005; Reichle et al., 2013; Reilly & Radach, 2006). RAN is another task that shares significant requirements with reading, especially oral reading, and has proved a valuable tool in educational, clinical and research settings. Our proposal builds on the E-Z Reader framework for understanding coordination of interacting cognitive and motor processes that control

gaze behavior in reading (Reichle et al., 2006). We adopt an additive approach to make direct comparison of behaviors associated with oral and silent reading and RAN, along with associations of each to measures of component reading skills.

C1.2 Fluency & RAN: Promise & Limitations

Reading Fluency

Oral reading fluency is a component of overall reading skill (e.g., Kim et al., 2011; Macaruso & Shankweiler, 2010; Petscher & Kim, 2011; Tilstra et al., 2009). A typical oral reading fluency assessment asks the subject to read a text passage aloud quickly and accurately, the response measure being the time needed to complete the passage, possibly with some penalty for errors, or the reading rate in words per minute (e.g., Wiederholt & Bryant, 2001). Several frameworks for understanding reading fluency emphasize the importance of coordination among the multiple processes required (Berninger et al., 2001; Breznitz, 2003; Breznitz, 2006; Perfetti, 1985; Shankweiler & Crain, 1986). At a minimum, the eyes must lead the voice sufficiently that there is time to process visual input into speech motor commands before they are needed, but not by so much that memory available to process and store those commands is overtaxed. Kim et al. (2011) examined the relationship of reading comprehension with both silent and oral reading fluency in first grade students and concluded that although silent and oral reading fluency are related skills their relationships to other reading relevant capacities suggest that they are at least partially dissociable. This is consistent with the fact that, while print is the input to both oral and silent reading, their output components differ.

A drawback to using global reading times to index fluency is that they say little about its detailed temporal characteristics and so provide a limited and unsatisfactory view of the reading process. Tracking eye-movements during reading is an established means of getting at that information (Rayner, 1998). Most eye-movement research on reading has focused on silent reading and the mature reader (Rayner et al., 2013), but see Barnes et al. (2015) for a recent analysis of gaze patterns during oral reading. In this new project, tracking eye-movements in both oral and silent reading within subjects will allow us to directly examine the inter-play of text and lexical properties with reader characteristics (e.g., Gong et al., 2015; Kuperman et al., 2010; Kuperman & Van Dyke, 2011; Valle et al., 2013). Eye-movements may reveal how reading demands are modified in shifting between oral and silent modes, as a function of differential demands on component skills (e.g., Kim et al., 2011; Valle et al., 2013). There are several existing mechanistic models of eye movements in silent reading, but none to our knowledge has been adapted to oral reading or RAN behaviors (e.g., Engbert et al., 2005; Reichle et al., 2012b; Reilly & Radach, 2006).

Rapid Automatized Naming

RAN has well established concurrent and predictive relationships to reading (Compton, 2003a, 2003b; Lervåg & Hulme, 2009). Subjects name items (e.g. 5 or 6 letters, digits, color swatches or line drawings) repeated in regular grid pattern in block random order (e.g., Denckla & Rudel, 1974; Wagner et al., 2013). The response measure is the time needed to name all items in the grid with few errors, similar to oral reading fluency (Wagner et al., 2013). RAN taps processes for visual scanning, object identification and naming, and the coordination among them. Some components overlap in obvious ways with oral reading, but RAN's complexity has made it difficult for researchers to reach a consensus about the nature of its relations to reading. Protopapas et al. (2013) propose that RAN taps a capacity for serial processing that is also important to reading, consistent with the generalized processing speed hypothesis of Kail and others (Kail et al., 1999; Kail & Salthouse, 1994; Wolf & Bowers, 1999). Another view is that RAN relies on object identification and object naming skills that also subserve printed word identification and word naming (Hulme & Snowling, 2012; Lervåg & Hulme, 2009). A third view, related to the naming and word ID hypothesis is that RAN taps phonological processing especially on the output side (Kail & Park, 1994; Wagner et al., 1994). These speculations are all consistent with the general idea that reading fluency and RAN draw upon capacities that are important to efficient lexical access (Perfetti, 1985), but the specific nature of the association remains uncertain (Powell et al., 2007). We point out that reading and RAN both require coordination among sets of processes, and that the particular processes involved in reading and RAN have a high degree of overlap (Berninger et al., 2001; Breznitz, 2003; Breznitz, 2006). This research exploits commonalities between reading and RAN to help resolve uncertainties in their causes. We do so by working toward a unified, implemented account of performance across tasks. Our main purpose is not to explain RAN as such, but a model of reading fluency that explicitly handles RAN will have distinct advantages over one that does not. It will be constrained by the need to accommodate both reading and RAN, and so may provide insight into the relationship between RAN and reading that will prove helpful in refining practical uses of RAN as an assessment.

C2. Instruments & Preliminary Work

Here, we introduce our approaches to eye-tracking, speech analysis, and simulation.

C2.1 Eye-tracking

Eye-tracking yields indicators of the moment-to-moment effort expended in the course of visual tasks (for reviews see: Rayner, 1998; Rayner & Juhasz, 2004). The volume and scope of developmentally oriented eye-movement work have been quite limited relative to research with adults (Blythe & Joseph, 2011; Rayner et al.,

2013). Reasons include both technical demands of eye-trackers and the fact that the devices available until recently have not been accommodating to child subjects (Rayner et al., 2013).

Rayner et al. (2013) note several developmental trends in children's eye-movements during reading. Fixation density drops by about 45% from 1st grade to 6th, declining only slightly more into adulthood. Average fixation time drops about 30% from 1st to 6th grade, and only slightly more into adulthood. Finally, the proportion of regressive (leftward) eye-movements decreases by about 21% from 1st to 6th grade, but then by another 36% from 6th grade to adulthood. These trends reflect improvements in the overall efficiency of the reading system. Word frequency and other lexical effects on eye movements in silent reading have been observed in children (Hyönä & Olson, 1995; Joseph et al., 2009; Joseph et al., 2013; Valle et al., 2013), similar to mature readers (Kuperman & Van Dyke, 2011, 2013).

Our own work with eye-tracking includes paradigms for investigating written language processing (Braze et al., 2006; Braze et al., 2002; Gong et al., 2015; Katsika et al., 2012; Sanchez-Alonzo et al., 2014) and spoken language processing using the 'visual world' technique (Braze et al., 2012; Kukona et al., 2016; Magnuson et al., 2011). The visual scanning component of RAN is possibly similar to that of reading. Preliminary work has verified that tracking eye-movements over RAN arrays yields data that is amenable to handling with our standard methods for working with gaze data (<https://github.com/davebraze/FDBeye>).

C2.2 Speech Analysis/Segmentation

There are but few examples of forced alignment (FA) being used for analysis of clinical or educational speech samples (Hogan-Brown et al., 2014; Hosom et al., 2004). Manual segmentation, a labor intensive approach, has occasionally been used (e.g., Laubrock & Kliegl, 2015; Lervåg & Hulme, 2009; Valle et al., 2013), but requires an estimated 1 hour for each minute of speech for detailed segmentation (DiCanio et al., 2013) and

inter-rater agreement is less than ideal (Hosom, 2009; Malfrère et al., 2003). Automated segmentation of speech samples has most often used an approach based on the amount of acoustical energy at each time point (Jones et al., 2013; Neuhaus et al., 2001a; Neuhaus et al., 2001b; Neuhaus & Swank, 2002). However, this method reportedly fails to identify about 13% of word boundaries in RAN data (Neuhaus et al., 2001a). It is likely to perform even less well when applied to oral reading, as fluent speech cannot be expected to show a reliable decrease in energy between words.

Therefore, we make innovative use of FA to parse speech recordings into constituent words and phones. FA is a standard technique in the field of automated speech recognition (Wightman & Talkin, 1997). The task of FA is much simpler than that of determining the content of unknown speech samples. An aligner takes two inputs, digitized speech and a transcript of that speech (in conventional orthography). Given these, FA automatically identifies boundaries of phones and words in the speech sample. First, the aligner determines the expected phone sequence for the entire sample by looking up words from the transcript in a pronunciation dictionary. Then, the most likely boundaries between speech sounds and words are predicted algorithmically based on a global 'best fit' to the entire recording (Wightman & Talkin, 1997). FA has good accuracy in comparison to manual segmentation (Hosom, 2009; Malfrère et al., 2003; Yuan & Liberman, 2008). Time indices in segmentation files can be aligned with time stamps in the eye-movement record to determine asynchronies between gaze targets and speech production, the eye-voice span (EVS; Halm et al., 2011; Inhoff et al., 2011; Morton, 1964). EVS provides another target for simulation work, beyond pure gaze measures. As we are working with scripted speech (oral reading or RAN), paired scripts and recordings are readily available. Where subjects deviate from the base script (by e.g., repetitions, hesitations/"um", coughing), we edit that subject's transcript to reflect the speech that they actually produced. We use the aligner described by Yuan & Liberman (2008), a well-vetted tool (http://www.ling.upenn.edu/phonetics/old_website_2015/p2fa/).

Figure 1 shows eye-voice span for a single RAN-letters trial. There, the eye leads the voice by as many as 3 items or as few as 0 (grey gaze points mean no speech was being produced). In our small pilot study (N=12), maximum EVS per subject for RAN-letters ranges from 2 to 4 items (m=1.06; sd=1.89), comparable to Hogan-Brown et al. (2014). The same method applies directly to speech produced during oral reading.

C2.3 Computer Simulations

Simulation work aims to account for interactions of visual processing, attention, and lexical processing that govern eye movements in silent reading. We begin with the established E-Z Reader (EZR) framework (Rayner et al., 1998), which has successfully reproduced many aspects of gaze behavior during reading (Pollatsek et al., 2006; Rayner et al., 2006; Reichle & Perfetti, 2003; Reichle et al., 1999; Reichle et al., 2009; Warren et al., 2009). The standard model for silent reading (EZR-S) is schematized in Figure 2 (Reichle et al., 2009, Figure 1b). It includes parameters that can be mapped to reading-related component skills. Lexical access occurs in two stages. L_1 is the time to recognize orthographic and phonological features of a word once attention is allocated to it, i.e., *decoding*. Completion of L_1 initiates calculation of an oculo-motor program (M_1) for shifting

1999). **Reading comprehension** is measured with the reading comprehension subtest of the WJIII battery. **Processing speed** is measured with Visual Matching and Decision Speed subtests from the WJIII-COG (Woodcock et al., 2001b). Processing Speed has been linked to differences in reading skill (Naples et al., 2012; Shanahan et al., 2006; Willcutt et al., 2005) and RAN (Kail et al., 1999). **Demographic information** is collected with the Haskins Child and Adolescent Background Questionnaire, including: educational history; reading habits; SES; personal and family history of learning disorders; history of neuropsychological disorders.

C3.3 Experiments

Experiments 1a, Reading Fluency and 1b Rapid Automatized Naming

Exp. 1a: Each subject reads 4 age appropriate narrative passages (different passages for each group). Passages for each group span a range of difficulty, posing few to modest demands on the reader. Three passages will be read orally and one silently. Presentation order is counterbalanced across subjects, as is the particular passage to be read silently. Further, the TL and FL groups will each read aloud one passage from the LR group; thus, subjects in the two older groups will read 5 passages each. The overlapping material serves to anchor group comparisons. Passages will be short, such that each fits on a single screen. Eye-movements are recorded for all reading trials, as well as speech for each oral reading trial, for about 17 hours of speech data from 660 (60x3+60x4+60x4) oral reading trials, assuming an average trial duration of 90 seconds.

Predictions: Between groups, we predict age-related improvements in both oral and silent reading rates (effect of parameter L_1 in Fig. 2). As fluency increases and decoding becomes less relevant as a limiting factor, we expect the *difference* between oral and silent reading speed to increase, resulting in a group (LR, TL, FL) by modality (oral, silent) interaction (parameter L_2).

Within groups, both oral and silent reading fluency are predicted to correlate with decoding skill (Ashby et al., 2013). We also expect increasing sensitivity (age-group) to word frequency across modalities, as reflected in local fixation times on each word (Joseph et al., 2013), and possibly decreasing influence of word length on fixation locations (Joseph et al., 2009). Older groups will also show longer eye-voice spans than younger ones due to more efficient reading systems and better coordination among subprocesses (Cain et al., 2004; Elman, 1993; Ouellette & Beers, 2010; Protopapas et al., 2007). Similarly, we predict fewer pauses and more strategic pause placement for older groups (e.g., more tightly linked to line endings). We will also compare EM data for oral and silent reading. Here we predict output demands from the articulation component of oral reading will lead to reduced modulation of EM by lexical factors like word frequency, relative to silent reading.

Another prediction is that increasing fluency, both within and across groups, will correlate with increases in the effect of context on both gaze time and speaking time. This will surface in the data as longer-range correlations within the time series for gaze and speech. Non-fluent text reading will be more like word list reading, where context is expected to have little effect. The process of fluent reading is predicted to exhibit long range dependencies, or context dependence, within each time series, also known as 1/f noise. This sort of effect in skilled performance is well-established in a number of domains (e.g., Gilden, 2001). We will use the method of fractal analysis for appraising these predictions (Diniz et al., 2011).

Exp. 1b: Each subject will perform 6 RAN tasks, 2 trials each of RAN letters, digits and colors. Materials will emulate the format of the CTOPP2 RAN tasks (Wagner et al., 2013), but subjects will view RAN arrays on a computer monitor so that eye-movements can be recorded. See §C2. We estimate an average of about 30 seconds per trial, and expect to gather about 9 hours of speech data from 1080 (180x6) RAN trials.

Predictions: Between groups, we predict improvements in RAN performance with age, with the largest increase between groups LR and TL (Meyer et al., 1998). Similarly, we predict fewer and shorter pauses in speech, and more strategic pause placement in older groups (Clarke et al., 2005; Cobbold et al., 2003; Georgiou et al., 2006). Connections between RAN, oral reading and decoding skill are expected to be strongest in the youngest group, becoming progressively weaker with development (Roman et al., 2009). However, within groups, we predict that associations between vocabulary and RAN, and between decoding and RAN, will be weaker than similar associations between those measures and oral reading, because of the lesser demands RAN places on item identification, and the lack of a meaning composition component in RAN.

Similarly, while more fluent RAN performance is expected to show increasingly 1/f pattern time series for gaze and speech, this effect should be much less pronounced than for reading due to the fact that a RAN series contains much less contextual information than does a printed text.

Pilot Work: We have collected data from 5 children, ranging from 6 to 11 years of age, using a protocol consisting of the skill measures described in §C3.2 and experiments 1a and 1b above. All children finished the protocol successfully. Time to complete the procedures ranged from 1 hour 20 minutes to 1 hour 40 minutes.

Testing Summary: Procedures will be administered in two sessions of 40 minutes to 1 hour each, on separate days; breaks are provided as needed. We estimate about 450 hours of participant contact over the 18 month data collection period of the project. See project timeline in §C5.

Experiment 2: Eye Movement Simulations

Three E-Z Reader variants (silent reading, EZR-S; oral reading, EZR-O; and RAN, EZR-R) will be used to

simulate eye-movements in each task. We can conduct two types of comparisons between recorded eye-movements in experiments 1a and 1b and the simulated data in the models. First, based on the silent reading performance of each age group, we tune values for parameters in EZR-S models, one for each group, to optimize fit to the average performance of the groups. We use a parametric approach to fitting simulated gaze time distributions to human data (e.g., Cousineau et al., 2004) as follows. Under a specific set of parameters and input texts, EZR-S generates a set of reaction times. The density function of that distribution is fitted to human data using a maximum likelihood approach. Best fitting models (sets of parameters) are located by iterative grid search through the parameter space, subject to plausibility constraints (e.g., Reichle et al., 1998). Group differences corresponding to parameter differences may reflect the influence of age and skill on reading behavior (Rayner et al., 2006; Reichle et al., 2013). Next, parameter settings established for EZR-S are used as fixed values for matching parameters in, EZR-O, which includes a superset of the processes/parameters contained in EZR-S. This places strict constraints on the relationship between the models for silent and oral reading, within each age-group. The extent to which parameters tuned for accurate simulation of silent reading allow for accurate simulation of oral reading performance (subject to additional constraints of EZR-O specific parameters), speaks to the viability of our assumptions about interactions of cognitive components operating in each domain. A poor fit would reflect shortcomings in our assumptions about relations between oral and silent reading as operationalized in EZR-S and EZR-O. Further, adjustments to model structure may be required to converge on a pair of models that afford reasonable fit to both oral and silent reading data. On reaching a satisfactory fit, we will make a subtractive comparison between parameters in the final EZR-O model and EZR-R (RAN) model, the latter containing a subset of parameters found in the former. So, by comparing simulation data generated from overlapping models with corresponding behavioral results, we can evaluate possible underlying explanations for correlations between RAN and reading.

C4. Methods of Analysis (Exp. 1a & 1b)

Eye-movements: Regions of interest (ROI) are defined for each token in RAN arrays, and for each word in reading tasks. For each ROI, we tabulate these gaze measures. First-pass duration is the summed duration of fixations within an ROI, provided that they do not result from a regressive EM. First-pass regressions are eye-movements that exit the current ROI to the left. Regression path targets are the leftmost extent of further regressions that follow the first-pass regressions. Speech is segmented using FA as described in §C2.2. Speech and EM signals are aligned to determine EVS and individual differences in EVS are evaluated in the context of reading related skills, while controlling for differences in oculo-motor control and raw articulation rate. Mixed effects regression is used to evaluate relationships of skill measures to gaze and speech data (Baayen et al., 2008; Dean & Nielsen, 2007; Pinheiro & Bates, 2000; Quené & van den Bergh, 2008).

Power Considerations: The proposed sample ($N=180$) is larger than those of most previous studies involving analysis of children's eye-movements (Joseph et al., 2013; Miller & O'Donnell, 2013; Rayner et al., 2013). Earlier studies, with $n < 50$, have found reliable (developmental) group differences in gaze patterns. Joseph et al. (2013) report a large difference in gaze time (Cohen's $f^2=0.36$) between children and young adults ($n < 30$ per group), aligned roughly with our youngest (LR) and oldest (FL) groups. With our proposed $n=180$ (60 per group) and $\alpha=0.05$, power to detect a between group effect of this size approaches 1. Granted, differences between our intermediate group (TL) and the others will be smaller, but assuming even a much more modest effect of $1/4$ that size ($f^2=0.09$), power to detect a main effect of group remains high ($\beta=0.90$). We are aware of only one study that reports group differences for eye-voice span (in RAN, Hogan-Brown et al., 2014). The population under study there is not directly on point, but the effect size is similarly large to that for gaze time (Cohen's $f^2=0.33$). Again assuming the effect in our study is but $1/4$ as large, power to detect a main effect of group on eye-voice span is respectable ($\beta=0.88$).

C5. Project Timeline

In months 1-3, we will finalize study materials, hire and train research assistants. Months 4-21 will be devoted to data collection. In this 18 month period, we will collect and process data from 180 participants, 10 per month. Midway through this period, we will perform preliminary analyses and present an interim report at a professional meeting. We will also begin preliminary simulation work at this time, expecting that we will have enough data in hand to inform that effort. Months 22-24 will be devoted to final data analysis; when completed, we will make another report to a professional meeting and submit findings for publication. Upon publication, all data (eye-tracking, speech files, speech segmentation files, and psychometric data) will be made available to the research community in accordance with open access principles.

C6. Project Summary

We will recruit 180 subjects from three age groups reflecting important periods in development of reading skill. We will collect about 26 hours of speech and EM data (9 hours of RAN, 17 hours of oral reading), as well as indicators of reading comprehension and component reading skills. Linked computational models of gaze behavior and the eye-voice span in reading and RAN will inform theory development. This research will help to resolve the uncertainties surrounding the question of how efficient coordination of reading subprocesses contributes to fluent reading.

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SUMMARY STATEMENT

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(Privileged Communication)

Release Date: 03/08/2017
Revised Date:

Application Number: 1 R21 HD090460-01A1

Principal Investigator

BRAZE, DAVID

Applicant Organization: HASKINS LABORATORIES, INC.

Review Group: LCOM
Language and Communication Study Section

Meeting Date: 02/09/2017
Council: MAY 2017
Requested Start: 07/01/2017

RFA/PA: PA16-161
PCC: CDBB -BM

Project Title: Reading Fluency Matters

SRG Action: ++
Next Steps: Visit http://grants.nih.gov/grants/next_steps.htm
Human Subjects: 30-Human subjects involved - Certified, no SRG concerns
Animal Subjects: 10-No live vertebrate animals involved for competing appl.

Project Year	Direct Costs Requested
1	150,000
2	125,000
TOTAL	275,000

++NOTE TO APPLICANT: Members of the Scientific Review Group (SRG) were asked to identify those applications with the highest scientific merit, generally the top half. Written comments, criterion scores, and preliminary impact scores were submitted by the assigned reviewers prior to the SRG meeting. At the meeting, the more meritorious applications were discussed and given final impact scores; by concurrence of the full SRG, the remaining applications, including this application, were not discussed or scored. The reviewers' comments (largely unedited by NIH staff) and criterion scores for this application are provided below. Because applications deemed by the SRG to have the highest scientific merit generally are considered for funding first, it is highly unlikely that an application with an ND recommendation will be funded. Each applicant should read the written critiques carefully and, if there are questions about the review or future options for the project, discuss them with the Program Contact listed above.

1R21HD090460-01A1 Braze, David

DESCRIPTION (provided by applicant): Fluency is an essential feature of skilled reading. Reading speed is an overt reflection of automaticity in decoding and similarly deft control over other component skills. There is considerable support for oral reading speed as a valid and reliable indicator of general reading skill. In fluent reading, whether oral or silent, processes of word recognition, comprehension, and eye movement control must be tightly coordinated, as characterized in several implemented models of eye movements over print (Reichle et al., 2013; Reilly & Radach, 2006; Engbert et al., 2005). Oral reading, in addition to those requirements shared with silent reading, places an additional demand on the reader: the need to produce accurate, prosodically appropriate speech in conjunction with the reading process itself. Both oral and silent reading rely not only on good control of component processes, but also on facile coordination of those processes (Berninger et al., 2001; Breznitz, 2003). Rapid automatized naming (RAN) is another fluency- like predictor of reading skills (see Bowey, 2005; Kirby et al., 2010; Hulme & Snowling, 2012; Cutting & Scarborough, 2006; Wolf et al., 2000). RAN's task demands overlap considerably with reading, especially oral reading (Denckla & Rudel, 1974). Yet, the nature of the connections between the two capabilities remains uncertain. This research exploits commonalities between reading and RAN to help resolve uncertainties in their causes. We do so by working toward a unified, theoretical account of performance across tasks. Our main purpose is not to explain RAN as such, but a model of reading fluency that explicitly handles RAN will have distinct advantages over one that does not. It will be constrained by the need to accommodate both tasks, and so may provide insight into relationships between the two that will prove helpful in refining practical uses of RAN as a reading assessment. Our approach is two-fold. First, we will assess relationships among oral and silent reading, and standard indicators of reading skill in three critical periods in the development of skilled reading: a learning-to-read group (7-8yo), a transition-to-fluency group (10-11yo), and a full-literacy group (17-18yo). We will evaluate developmental differences between groups and individual differences within groups. We will apply new ways to investigate RAN performance and oral and silent reading fluency derived from analysis of gaze behavior, and of asynchronies in gaze and speech behaviors produced during these tasks (Jones et al., 2008). We make novel use of speech processing technology to facilitate alignment of speech and gaze signals to accommodate the large volume of speech data generated by the project. Second, we will implement a unified model of coordination among component processes for oral and silent reading (Reichle et al., 2009; Reichle, Pollatsek, et al., 2012). A successful unified model will serve as a testbed for investigating structural relationships among oral and silent reading, RAN and component skills.

PUBLIC HEALTH RELEVANCE: This project aims for better theoretical understanding of text reading fluency in 3 developmental periods critical to literacy acquisition: learning-to-read, transition-to-fluency, full-literacy. It makes novel use of timing relationships between eye-movements and speech, and adapts existing models of eye movements over text to illuminate connections among the targeted reading behaviors and rapid naming. This research will provide theoretically motivated, computational model of reading fluency and the cognitive conditions that support it.

CRITIQUES: The written critiques of individual reviewers are provided in essentially unedited form below. These critiques were prepared prior to the meeting and may not have been revised afterwards.

CRITIQUE 1

Significance: 5
Investigator(s): 1
Innovation: 5
Approach: 5
Environment: 1

Overall Impact: The proposed research activities seek to assess the relations between oral and silent reading at three stages of development, and to develop a computational model that covers both silent and oral reading, with the E-Z Reader model as a starting point. The participants will undergo eye-tracking during silent reading and oral reading, and during execution of a rapid automatized naming (RAN) task. The new model of oral reading will include parameters relating to speech motor planning and speech production. Because RAN performance correlates with reading fluency, a model that predicts and explains both RAN performance and reading performance has advantages over a model that predicts and explains only reading performance. The idea appears to be that eye-movement control and cognitive processes are in a reciprocal relationship; and that RAN data provide an index of process coordination, which is the degree to which readers can use the outcome of a set of processes to decide where and when to move the eyes. Hence, modeling process coordination in a way that captures RAN task performance on top of silent reading may lead to better understanding of reading itself. The strengths of the application are mitigated by the absence of a strong case for innovation. Revising the E-Z Reader model to accommodate RAN and oral reading data is incremental rather than transformative. Qualitative differences between natural reading and the RAN task may limit the utility of generalizing a model from either domain to the other. A number of individual difference approaches successfully predict reading outcomes without the incorporation of RAN performance. It is not clear whether a RAN-based approach should supplant those other approaches. Overall, the proposed activities have a modest likelihood of exerting a powerful, sustained influence on research in reading.

1. Significance:

Strengths

- Developing better theories of reading silently and aloud is a worthy basic science enterprise.
- Developing better tools for analyzing spoken protocols may facilitate research more broadly.

Weaknesses

- It is not clear that developing a unified account of reading silently, reading aloud, and rapid automatized naming adds value over and above having well-supported accounts of each individually.

2. Investigator(s):

Strengths

- The research team has strong background and experience in reading, individual differences, and the application of forced alignment.

Weaknesses

- No major weaknesses noted.

3. Innovation:

Strengths

- Comparing and contrasting silent reading skill, oral reading skill, and RAN performance is a novel approach. It may be possible to identify process coordination issues using RAN data that correlate with eye-movement control issues during silent and oral reading.
- The application of the forced alignment technique may produce a software tool that will be of value to speech production and comprehension researchers.

Weaknesses

- The idea that perceptual span/foveal attention load varies with text difficulty relative to reading skill is well supported by the existing literature.
- Extending E-Z Reader to accommodate oral reading performance is incremental rather than transformative.

4. Approach:

Strengths

- The validation of the forced alignment technique using RAN data as the test bed is a strength of the approach.
- The participant sample sizes appear to be sufficient for individual differences analysis.

Weaknesses

- It is not clear whether RAN performance can supplement or replace other precursor skills (phonological awareness), other concurrent knowledge or capabilities (vocabulary knowledge), and experience as predictive and explanatory constructs in reading.
- Important theoretical constructs, like general reading skill, are left underspecified.
- Group differences may be confounded with cohort status.
- There may be important differences between natural, extended text and RAN stimuli that limit the ability to generalize across tasks. For instance, higher order discourse structures are typically present in written narrative, but not in RAN stimuli.
- Since E-Z Reader is a model of eye-movement control, and oculomotor control plays a subsidiary role in literacy development, the connection between a more comprehensive eye-movement control model and reading (comprehension) outcomes is indirect.
- The application views RAN performance as being linked in some way to efficient lexical access. That being the case, RAN data may be superfluous. If RAN is a proxy for fluent decoding ability, more accurate prediction of reading outcomes might be derived from a model that incorporates a direct measure of word decoding.

5. Environment:

Strengths

- The research environment is highly conducive to the proposed research activities.

Weaknesses

- No major weaknesses noted.

Protections for Human Subjects:

Acceptable Risks and/or Adequate Protections

- The study procedures present no more than minimal risk. Adequate safeguards are envisioned.

Data and Safety Monitoring Plan (Applicable for Clinical Trials Only):

- Not Applicable (No Clinical Trials)

Inclusion of Women, Minorities and Children:

- Sex/Gender: Distribution justified scientifically

- Race/Ethnicity: Distribution justified scientifically
- For NIH-Defined Phase III trials, Plans for valid design and analysis: Not Applicable
- Inclusion/Exclusion of Children under 18: Including ages <18; justified scientifically
- The participant samples are appropriate to the specific aims.

Vertebrate Animals:

Not Applicable (No Vertebrate Animals)

Biohazards:

Not Applicable (No Biohazards)

Resubmission:

- The resubmission has addressed many of the concerns raised in prior review. Concerns regarding the theoretical importance and practical value of extending E-Z Reader to handle oral reading and RAN performance remain.

Authentication of Key Biological and/or Chemical Resources:

Not Applicable (No Relevant Resources)

Budget and Period of Support:

Recommend as Requested

CRITIQUE 2

Significance: 2

Investigator(s): 1

Innovation: 4

Approach: 3

Environment: 1

Overall Impact: Overall, this application plans to develop new conceptual models that incorporate RAN, oral reading and silent reading arguing that this will provide a more precise model of reading, measured via eye movement. The research is incremental, which is fine. However, it is not clear how these findings will address the very real public health challenge of poor literacy skills and their sequelae. The investigators are strong and well qualified to conduct this research, as are the facilities. For the most part, this application is responsive to prior review.

1. Significance:

Strengths

- Fluency is an important but only weakly understood aspect of reading and reading proficiency.
- RAN and why it predicts reading is also not well understood.

- The study includes children at different developmental phases of reading from learning to read to reading to learn. The project will also measure other key aspects of literacy including vocabulary, decoding, and comprehension, so it should be able to capture individual differences.
- The aim is to develop computational models.

Weaknesses

- The application does not address how the project will control the difficulty of the text children will read, which has real implications for fluency – the more difficult the text with regard to unfamiliar words and complex syntax, the slower and with more regressions children's reading will be.
- There is prior research on silent versus oral reading that is not considered but that would help elucidate these arguments.

2. Investigator(s):

Strengths

- This is a strong team that is well qualified to conduct the proposed research.

Weaknesses

- No major weaknesses noted.

3. Innovation:

Strengths

- This research, while incremental, has the potential to improve our understanding of fluency, RAN, and individual differences.
- The use of speech recognition technology is innovative.

Weaknesses

- It is not clear how the findings will impact the improvement of literacy, which is a serious public health concern.

4. Approach:

Strengths

- Overall the study design and methods are strong and will meet the aims of the investigation.

Weaknesses

- It is not clear how the project will control the difficulty of the text, which will influence fluency.
- RAN also predicts language skills, and it is not clear how the proposed models will incorporate that aspect of RAN.

5. Environment:

Strengths

- Haskins Labs are notable for their research environment.

Weaknesses

- No major weaknesses noted.

Protections for Human Subjects:

Acceptable Risks and/or Adequate Protections

Data and Safety Monitoring Plan (Applicable for Clinical Trials Only):

- Not Applicable (No Clinical Trials)

Inclusion of Women, Minorities and Children:

- Sex/Gender: Distribution justified scientifically
- Race/Ethnicity: Distribution justified scientifically
- For NIH-Defined Phase III trials, Plans for valid design and analysis: Not applicable
- Inclusion/Exclusion of Children under 18: Including ages <18; justified scientifically

Vertebrate Animals:

Not Applicable (No Vertebrate Animals)

Biohazards:

Not Applicable (No Biohazards)

Resubmission:

- The application is responsive to the concerns raised in prior review and the application is much improved.

Authentication of Key Biological and/or Chemical Resources:

Not Applicable (No Relevant Resources)

Budget and Period of Support:

Recommend as Requested

CRITIQUE 3

Significance: 4

Investigator(s): 4

Innovation: 3

Approach: 4

Environment: 2

Overall Impact: The application addresses the components of oral and silent reading fluency in three age ranges that span a major period of reading development. The experimental work and subject population is sound. The developmental data alone may have some value. The Principal Investigator has a modest publication record working in the reading and speech fields. The significance of the modeling effort is still not clear, and it is not convincing that the parameter additions and their curve fitting will advance the understanding of fluency and individual differences in reading.

Protections for Human Subjects:

Acceptable Risks and/or Adequate Protections

Data and Safety Monitoring Plan (Applicable for Clinical Trials Only):

- Not Applicable (No Clinical Trials)

Inclusion of Women, Minorities and Children:

- Sex/Gender: Distribution justified scientifically
- Race/Ethnicity: Distribution justified scientifically
- For NIH-Defined Phase III trials, Plans for valid design and analysis: Not applicable
- Inclusion/Exclusion of Children under 18: Including ages <18; justified scientifically

Vertebrate Animals:

Not Applicable (No Vertebrate Animals)

Biohazards:

Not Applicable (No Biohazards)

Authentication of Key Biological and/or Chemical Resources:

Not Applicable (No Relevant Resources)

Budget and Period of Support:

Recommend as Requested

Footnotes for 1 R21 HD090460-01A1; PI Name: Braze, David

NIH has modified its policy regarding the receipt of resubmissions (amended applications). See Guide Notice NOT-OD-14-074 at <http://grants.nih.gov/grants/guide/notice-files/NOT-OD-14-074.html>. The impact/priority score is calculated after discussion of an application by averaging the overall scores (1-9) given by all voting reviewers on the committee and multiplying by 10. The criterion scores are submitted prior to the meeting by the individual reviewers assigned to an application, and are not discussed specifically at the review meeting or calculated into the overall impact score. Some applications also receive a percentile ranking. For details on the review process, see http://grants.nih.gov/grants/peer_review_process.htm#scoring.

MEETING ROSTER
Language and Communication Study Section
Biobehavioral and Behavioral Processes Integrated Review Group
CENTER FOR SCIENTIFIC REVIEW

LCOM
02/09/2017 - 02/10/2017

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* Temporary Member. For grant applications, temporary members may participate in the entire meeting or may review only selected applications as needed.

Consultants are required to absent themselves from the room during the review of any application if their presence would constitute or appear to constitute a conflict of interest.