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GAZE INTO LITERACY:

THE POTENTIAL OF EYE MOVEMENT ANALYSIS FOR ASSESSING CHILDREN'S WORD READING SKILLS IN ECOLOGICAL CONTEXTS

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Gaze into literacy: The potential of eye movement analysis for assessing children's reading skills in ecological contexts

Thesis for Doctoral Degree (Ph.D.)

By

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Dedicated to

Freya, Timothée, Maya and Jammaria and everyone in my family

and

the memory of Ida Cecilia Bergman.

Popular science summary of the thesis

Reading is a complex skill that allows us to turn printed words into meaningful language. This ability is crucial for almost everything we do in life. If someone has trouble reading, it can seriously affect their quality of life, academic development, mental health and participation in society. Once we learn to read well, recognizing words when we see them feels natural and effortless. We rarely think about the process itself. In reality, the reading process is an intricate interplay between psychological and physiological systems. When reading, our eyes move in a specific pattern: we quickly glance at (almost) each word and make rapid eye movements from one word to the next. Very small, but measurable variations in our eye movements give a detailed look into how written language is processed in our minds. Research has shown that there are specific variations to children's eye movements during reading – such as needing more time to look at a word to be able to interpret it - compared to adults. As children become more fluent readers, their eye movement patterns gradually change to look more like that of adults. That means that children's eye movements vary with their reading skill, but this relationship is not fully understood in early learners and is usually studied in lab settings.

This doctoral project explored the relationship between children's eye movements and reading skill in real-world contexts in school-age children. Eye movement data and reading test scores were collected from children in their natural school environment. The first study found patterns in children's gaze behavior during reading similar to past research but with more variability in eye movement data. The time children spent looking at words was strongly linked to tests that measure word processing skills. As children aged, changes in their eye movements correlated with development of their reading skill. Eye movements explained variation in reading ability to the same extent as, and in some cases more than, school grade. The second study showed that eye movements can be used to explain differences in reading ability one year later, meaning that eye movements can give indications of which readers will struggle later on. The third study found that there were signs in the early eye movements of children with lasting difficulties. They looked at words significantly longer while reading in second grade, compared to peers who had poor reading results but who would improve to average level by third grade. This suggests that eye movements can be used to understand which children who have poor abilities important to

reading and those who have poor results for other reasons, such as limited experience with written language.

The work in this thesis showed that there is a link between children's eye movements and ability to process words, which is measurable in the children's everyday school environments. Moreover, it shows that eye movement analysis has potential for assessing children's reading ability, in terms of both present and later skill, and help tell apart children with lasting reading difficulties from those whose reading improves. However, it is important to consider that the school environment is less controlled than laboratory settings, which makes it more difficult to draw conclusions based on these findings. Other factors, such as the choice of eye movement measures and large group of participants with varying backgrounds influence the certainty of the conclusions in this thesis. Further research could benefit both knowledge development about children's eye movements and reading skill and the understanding about how research findings in this field can be implemented in the school environment.

Abstract

Children's reading proficiency is reflected in their eye movements during reading, a subject predominantly explored in experimental settings. This doctoral project investigates these dynamics within naturalistic environments. Word reading assessments and eye movement measures were collected from Swedish schoolchildren, revealing patterns consistent with prior research but with increased variability in eye movement data. Analyses showed age-related changes in eye movement characteristics correlating with word reading outcomes. The link between mean fixation duration and tests reliant on lexical processing was particularly strong. Eye movements explained variance in multiple word reading tasks and accounted for nearly half of the overall variance in word reading skill one year post-recording. Among second grade students with below-average performance, those persistently scoring below average in third grade exhibited significantly longer fixations than those who would improve, indicating early eye movements can be used to differentiate between children with persistent difficulties and eventual improvement. The findings of this thesis reinforces previous findings in the participants' school environments, suggesting that it is feasible to analyze connections between children's eye movements and reading development under ecologically valid circumstances. Results show that eye movement analysis could be useful to reading assessments, as it offers a means to index children's word reading ability in concurrent and longitudinal perspectives and can be used to detect true skill deficits. However, the effects of limited experimental control should be considered upon reviewing results. With continued research and careful implementation, eye tracking holds promise for early education practices.

List of scientific papers

I. **Andrea Strandberg**, Gustaf Öqvist Seimyr, Mattias Nilsson, Per Östberg
Eye Movements during Reading and their Relationship to Reading Assessment Outcomes in Swedish Elementary School Children
(Journal of Eye Movement Research)

II. **Andrea Strandberg**, Gustaf Öqvist Seimyr, Mattias Nilsson, Per Östberg
Eye Movements are Stable Predictors of Word Reading Ability in Young Readers
Frontiers in Education

III. **Andrea Strandberg**, Gustaf Öqvist Seimyr, Mattias Nilsson, Per Östberg
Early Eye Movement Characteristics of Children with Persistently Poor Word Reading Ability
Submitted

Contents

List of abbreviations

ms	milliseconds
RAN	Rapid Automatized Naming
RTI	Response to intervention

1 Introduction

Eye movements offer a sensitive and fascinating window into cognitive processing (Gidlöf et al., 2013; König et al., 2016; Rayner, 1977). Our gaze behavior is associated to specific mental operations, which makes eye tracking an exceptional investigative tool for anyone seeking to gain insight into human behaviors. The range of applications is extensive, including research in fields such as neuroscience, psychology, finance, and education (Hermens et al., 2013; Klein & Ettinger, 2019; Mason et al., 2014; Mcdonald et al., 2015; Radach, et al., 2003; Robinski & Stein, 2013.). Eye movements allow scientists to probe individuals' mental processes in real-time and generate objective estimations of cognitive activities. Due to its high temporal and spatial sensitivity, eye tracking is an optimal technique for studying complex processes (Blythe, 2014).

Reading is a remarkable accomplishment and an exceptional case of information processing. It relies on the smooth coordination and interpretation of information from several psychological and physiological systems (Clifton et al., 2016; Henderson et al., 2015; Rayner, 1998, 1978). Proficient readers look at the printed patterns that make up letters, words and sentences, and are able to encode them with information and generate meaningful language. The ability to decipher text is fundamental in almost all areas of life and impairments to this capacity severely affect individuals' quality of life, their ability to participate in society, academic achievements and emotional wellbeing (Daniel et al., 2006).

Once the quite painstaking activity of learning to read has reached a point where words can be encoded in a nearly automatic manner, few think about what we actually are doing as we read. Word processing becomes almost reflexive - one cannot help but read a word when presented with one. In the analysis of our eye movements, a distinct pattern emerges as we work through a text. We look at individual words for short periods and make very fast, ballistic eye movements in between (Rayner, 1977, 1978; Rayner & McConkie, 1976).

In reading research, scientists utilize eye tracking to observe the stop-motion-like pattern indicative of underlying cognitive processes. It has played a crucial role in advancing our understanding of the reading process, as one of the few behavioral measures available to investigate it. Lexical processing is widely understood as the operating mechanism guiding eye movements in reading.

With exception of sensory processing during Braille reading, eye movements are an integral part of the process. Uniquely, it contributes with information on reading as it happens – in real time, unlike offline evaluations which provide insights into reading once it has been completed.

For several reasons, eye movement research into reading development has historically been scarce (Clifton et al., 2016; Rayner, 1998). Due to technical and methodological challenges, it was not until recent decades that studies with young, developing readers caught some momentum. Since then, it has been shown that eye movement analysis provides an accurate and precise index of the reading process as it unfolds in children (Blythe, 2014; Blythe et al., 2009, 2015; Rayner, 1986; Reichle et al., 2013a). During reading development, children need progressively less time to look at words to be able to decipher their meaning. They move their gaze longer distances across the text and the need for corrective rereading decreases. The subjective ease that the child experiences as they read as well as their progress as readers is reflected in their eye movements (Rayner, 1986; Suk et al., 2022), which has sparked interest in possible applications to educational assessment perspectives on reading. However, little is known about the relationship between developmentally driven changes in eye movements and children's text processing unfolds in authentic learning environments.

2 Literature review

The aim of this literature review is to contextualize the present studies and identify areas in the research on children's eye movements during reading and reading development where knowledge is limited, as well as challenges in addressing reading difficulties within educational settings. First, I address eye movement research in reading from the last decades, with insights into theory regarding the cognitive processing of text. Findings from adult studies and investigations into children's eye movements and reading development are outlined. Subsequently, development of reading ability, reading difficulties and assessment of reading are summarized. Finally, applications of eye tracking technology in education are addressed.

2.1 Eye movements in reading

In the dawn of cognitive psychology in the 1960s, reading became a popular research subject among scientists in education and psychology. Concurrently, modern practices in eye tracking had been developed. The most important

technological development was the implementation of computers, which made analysis easier and results more accurate. During the preceding decades, researchers used other techniques that were veritably impossible to use with children (van Gompel et al., 2007). In 1960s and onward the technique shifted to recording the reflection of infrared light beams in the eye and computers helped with analysis. This method has been further developed and improved during the last centuries and remains the approach today (Liversedge et al., 2012).

Certain features of eye tracking methodology have made it suitable to investigate complex processes such as reading. The shift from the preceding, more behaviorally guided, centuries resulted in significant theory development from the nineteen seventies and onward (Rayner, 1978).

Earlier during the same century, Buswell had contributed to the field of educational psychology with pioneering work in eye movement research (Buswell, 1937; Robertson, 1996), showing that visual skills and reading skills are unrelated and the eye moves differently during silent and oral reading. In the 1970's, researchers continued to investigate what guides the reader's gaze through the text. Through manipulations of the stimuli, studies showed how small variations in the subjects' eye movement-responses were inextricably linked to cognitive processes (König et al., 2016; Rayner, 1998, 1977, 1978, 2009). The basic premise is that these subtle variations reflect underlying mental operations necessary for encoding text (Carpenter & Daneman, 1981; Just & Carpenter, 1980). Most of the available information related to a word is processed immediately during a fixation. Consequently, readers fixate on a word long enough to construct a mental representation of the word, extract it's meaning and start the process of analyzing the word's position within the sentence structure to understand its grammatical components and their relationships (Ehrlich & Rayner, 1983). Long, frequent gazes are interpreted as signals of either increased complexity or increased processing difficulties (Blythe et al., 2009). Thus, monitoring the direction and duration of eye movements offers insights into the temporal dynamics of cognitive operations (Just & Carpenter, 1980). Previous and later work has supported this idea (König et al., 2016; Rayner, 1977; Rayner & McConkie, 1976; Reichle et al., 2006). Variations in our gaze patterns are accordingly considered the effects of processing difficulties rather than their cause (Reichle et al., 2009; Yang, 2012).

While subjective intuition suggests our eyes smoothly move in a straight line across the text during reading, tracking the actual gaze movements contradicts

that assessment. Instead, we stop and fixate the pupil at one word at a time and make fast gaze movements in-between (Clifton et al., 2007; Liversedge & Findlay, 2000; McConkie & Rayner, 1975; Reichle et al., 1998). Scientists have created measurements of spatial and temporal character known as fixations (the stops) and saccades (the rapid movement from one word to the next), which capture this behavior (Inhoff et al., 2019; Inhoff & Rayner, 1986; McConkie & Rayner, 1975; Rayner et al., 1982). Fixations are considered indices of what is currently being processed and comprehended (McConkie & Rayner, 1975). The first look – e.g., the first fixation on a word is representative of the initial processing of that word. That is, the encoding of the visual stimulus with lexical information. Syntactic and semantic concepts are activated and integrated with the meaning of the text that has been read up until that point (Ehrlich & Rayner, 1983; Inhoff, 1984a). An average fixation is approximately 250 milliseconds (ms) in adult, proficient readers, but can be as short as 60 ms (McConkie & Rayner, 1975; Rayner, 1998). Sometimes we make additional fixations on a word to improve or revise incorrect grapho-phonemic, syntactic, or semantic interpretations (Blythe, 2014; Blythe et al., 2009, 2015; Reichle et al., 2013b). The total time an individual spends fixating a word is reflective of all the processes triggered by that word. During this initial phase of text processing, our visual encoding system determines whether a word will be identified (Rayner, 1998, 1978; Rayner & McConkie, 1976). Once threshold values for identification are reached, the programming of a saccade to upcoming print is triggered. The average forward saccade is approximately 4-5 degrees and occur approximately 3-5 times per second in adult readers (Pan et al., 2023). Recent research suggests that low-level information from different visual areas (i.e., presaccadic and postsaccadic regions) is available and integrated during a saccade, contributing to the perception of continuous reading (Fabius et al., 2020; Pan et al., 2023).

Saccades also run in the opposite of the reading direction, caused by a need to revise the encoding and interpretation of previous text. In proficient readers, regressions make up approximately 15-20 % of all saccades (Inhoff et al., 2019; Pynte et al., 2008). The area of effective vision during reading, called the perceptual span, covers approximately 3–4 characters to the left and 14–15 characters to the right around the point of fixation in proficient readers of English (Rayner, 2014). It is asymmetrical to the right of the point of fixation in English, Swedish and other orthographies where one reads from left to right. The perceptual span is the region from which we process information during fixations,

but encoding and interpretation are further supported by preview of what comes next (parafoveal preview) which allow readers to identify differences in letters and retain other visual cues to the right of the perceptual span (Rayner et al., 1982; Reichle et al., 2013a).

While eye movements during reading and their cognitive underpinnings in proficient readers are well documented (Rayner, 1998, 1978; Hyönä & Kaakinen, 2019), children's eye movements in reading processes have not been as extensively studied due to methodological challenges and a historical focus on adult readers. However, due to technological developments and the growing recognition of the significance of early reading development, research on young readers has increased since the 1980s (Blythe, 2014). Many studies have highlighted consistent, developmental changes in eye movement patterns in young readers during reading development (Blythe et al., 2011; Kim et al., 2019; Prado et al., 2007; Rayner, 1986; Suk et al., 2022). As a child's reading proficiency advances, there are observable changes in the coordination of cognitive, visual, and oculomotor functions (Reichle et al., 2013; Blythe & Joseph, 2011) with consistency across various educational frameworks, writing systems, and languages investigated thus far (Reichle et al., 2013; Clifton et al., 2016). This means, children's eye movements in reading are similar to those of adults with regards to quality, with quantitative differences. Generally agreed-upon, normative values from children's data is lacking in the literature as of today (Wertli et al., 2022). However, it is well-known that children have longer fixation durations, shorter forward saccades and make more frequent regressions than adults, and that there is a gradual change to these measures that corresponds to children's progress as readers (Blythe et al., 2006, 2009). Additionally, the perceptual span grows throughout reading development and children experience parafoveal preview benefits linear to their reading fluency (Rayner, 2014). Similarly to proficient readers, children's gaze behavior during reading is sensitive to the linguistic aspects of the stimuli (Häikiö et al., 2011, 2015, 2018; Joseph et al., 2013; Tiffin-Richards & Schroeder, 2015) Cross-language comparisons have showed that eye movements are affected by the language-specific characteristics of the text during reading development, but that differences are attenuated as readers become more proficient (Schroeder et al., 2022). At approximately twelve years of age, children's eye movement characteristics resemble adult's eye movements during reading (Rayner, 1998).

The accumulated eye movement research into children's reading has taught us a good deal about reading development. However, little is known about how these reflections of text processing unfold in real-life situations. Examining children's gaze behaviors in settings that intentionally mimic everyday contexts would allow inferences about how a more variable context affects their eye movements during reading. The possible effect of limited experimental control is mostly unexplored, with few exceptions (see Vorstius et al., 2014). Research thus could address the fundamental question of whether it is feasible to analyze children's eye movements during reading tasks in variable environments.

2.2 Reading ability

2.2.1 Reading development

In a sense, the development of reading ability starts during infancy and is ongoing until about third or fourth grade. Very early, children's phonological awareness start to form, meaning that they start to become aware of the sounds of spoken language by hearing people around them communicate verbally and vocally. From approximately three or four years of age, children develop abilities to detect, manipulate and blend phonological information (Anthony et al., 2005; Anthony & Lonigan, 2004; Wolff & Gustafsson, 2015) Phonological awareness is essential for developing strong reading and spelling skills. Knowledge of the sounds in spoken language and how they can be manipulated supports the process of making connections to print. Before transitioning to preschool class (the year the child turns 6, according to educational practices in Sweden) children start to learn about how speech sounds are represented by letters in words (phonemic awareness). The process of conscious effort to make the connections between sounds and printed language can be laborious. That knowledge must be consolidated in memory to a point where sound-print correspondence is automatically accessible upon reading. During reading development, the quality of these connections progresses from a non-alphabetic to full grapho-morphemic level (Ehri, 2005). Phonics instruction initially focuses on small units (letters). Gradually, children learn about how letters can be combined in syllables and words, and how to spell and pronounce larger units of print. Through a series of intersecting phases, children acquire knowledge about word spellings to their pronunciations. This process, referred to as orthographic mapping, facilitates sight-word reading and vocabulary learning (Ehri, 2014a). At the juncture of approximately third or fourth grade and higher grades, fluent reading and text comprehension becomes imperative to access further learning opportunities.

2.2.2 **Reading difficulties**

Reading difficulties, also known as dyslexia or developmental learning disorder with impairment in reading, (Word Health Organization, 2019) affects approximately 3-20 % of the population (Peterson & Pennington, 2015; Snowling, 2013) and is characterized by persistent challenges in acquiring proficient reading skills. Sometimes, specifiers such as "despite adequate intelligence and educational opportunities" are used, due to the assumption of a discrepancy of intelligence and reading achievement as a marker of specific reading difficulties. Recent work indicates that response-to-intervention focused approaches (RTI; i.e. the extent to which the individual improves in response to remediation) might provide a more useful characterization (Justice, 2006; Vaughn et al., 2010), but the roots of these issues are not fully understood.

The definition of reading difficulties lacks a universally agreed-upon description, with differing perspectives offering more or less extensive interpretations of its conceptual foundations. The operational criteria vary as well, meaning that the choice of classification system can influence who gets the diagnosis of reading difficulties (Di Folco et al., 2022). Impaired word reading ability is the most central and frequently acknowledged issue. Broader perspectives often encompass deficiencies in phonological processing and phonemic awareness, along with fluency issues (Parrila & Protopapas, 2017). Phonemic awareness, rapid automatized naming (RAN) skills and fluid intelligence are connected to latent factors reflecting reading ability from an early age (Wolff et al., 2023) when reading skill is limited. Training in phonological awareness and RAN has effect on word reading skill, which suggests causal roles (Stappen & Van Reybroeck, 2018a; Wolff & Gustafsson, 2022).

There is variation in the outward presentation of these issues in developing readers. Deeper level. phonologically caused difficulties versus surface dyslexia, where poor performance mainly concerns orthographic tasks, may have different impacts on performance (Wolff, 2005.) Children with reading difficulties may struggle to phonologically decode words, recognize sight words, understand word meanings and comprehend text (Roitsch & Watson, 2019; Snowling et al., 2020). During reading tasks, there are variations in their eye movements indicative of challenges in processing written language (Rayner, 1985). They tend to have longer fixation durations, higher proportion of fixated words (proficient readers tend to skip some), more frequent regressions, and shorter forward saccades compared to typically developing readers. Eye movements of young, struggling readers

resemble those of even younger, reading-level-matched controls rather than their age-matched peers. Additionally, slow readers have smaller perceptual spans and letter identity spans (the area within the text from where visual information about letter identity can be extracted) compared to faster readers (De Luca et al., 2002; Häikiö et al., 2009).

Reading difficulties can significantly affect academic performance and pursuits, and typically persist into adulthood. There may be significant consequences that extend beyond academic challenges, affecting employment opportunities, access to important information about individual matters or society, as well as social and emotional wellbeing (Livingston et al., 2018). Reading difficulties in young individuals are linked to a higher risk of suicidal ideation and attempts, even when controlling for sociodemographic and psychiatric variables (Daniel et al., 2006). Despite the existing knowledge about the cognitive underpinnings of learning to read, as well as the needs of children with reading difficulties the average age of diagnosis with reading difficulties in Sweden was 13 years (in 2014; SBU, 2014).

2.3 Assessment of word reading ability

In educational settings, the assessment of students' skills and needs are handled by teachers, special-educations teachers, school psychologists or speech and language pathologists. In young children, reading is usually evaluated in a regular and systematic manner, to monitor their development. Skill monitoring through screening typically involves a brief test session conducted within educational settings, exemplified by assessments like Läskedjor-2 (a validated Swedish screening material; Jacobson, 2015). Individual in-depth assessments, which are more time-consuming, are predominantly carried out in external clinics by speech and language pathologists. However, there is an overlap of tests used in educational and clinical environments. The test outcomes are often offline proxies to cognitive constructs or skills that support or represent reading. Reading assessments tend to comprise measures of phonological processing time (such as Rapid Automatized Naming, RAN; (Denckla & Cutting, 1999a; Denckla & Rudel, 1976; Wolff, 2014), phonemic awareness, oral reading accuracy and some measures of fluency and text comprehension (Grabe & Jiang, 2013; Hudson et al., 2005). Reading of pseudo words and correctly spelled words can be included since both phonological decoding and sight words processes are affected in children with RD (Bazen et al., 2020; Peterson et al., 2014).The choice of tests is ideally guided by the accumulated knowledge about how several underlying processes and skills interact during reading. Reading assessments often involve

several purposes, including assessing the potentially underpinning issues, how deficits in those skills encumber fluent reading (testing word reading and/or comprehension) and what pedagogical and/or compensatory interventions might be relevant.

Ideally, the outcomes advise the assessor about individual student needs and ultimately inform efficient instruction programs. However, in some cases the scientific assessments of the tests have been reported deficient (Andresen & Monsrud, 2022; SBU 2014), which can compromise their effectiveness and the assessor's possibilities to draw trustworthy conclusions based on its results. Elementary school teachers spend an increasing amount of time on assessment. The compulsory assessment provided by The National Agency for Education has been publicly criticized by researchers, claiming it is both time-consuming and provides too coarse a net, and thereby fails to identify many students who need further assessment and intervention (at the time of printing of this thesis, there were no scientific publications available, but see Hallin & Fridolfsson, 2022). In their 2014 systematic literature review, Swedish Council on Health Technology Assessment found that more than 50 different tests are used to assess reading difficulties and reported issues with the scientific evaluation of every assessment included in the review. A need for longitudinal studies which identify methods to reliably predict reading difficulties has been reported (SBU, 2014). Word recognition and phonological processing skills are promising predictors of reading skill, but the predictive capacity of skill tests is rarely evaluated, with regards neither to current nor longitudinal perspectives (Peterson & Pennington, 2015; Stappen & Van Reybroeck, 2018a).

Another challenge related to assessments is the occurrence of floor effects, a phenomenon frequently encountered in evaluating word reading skills. This arises from the attempt to quantify young children's proficiency in a domain in which they have had limited experience (Catts et al., 2009). Among kindergarten-age children (5-6 years; approximate equivalent to Swedish first year of preschool education, "förskoleklass") and early school-age children, including monolinguals for whom these assessments are designed, there is often a notable underperformance on tests evaluating word reading abilities during their initial academic years due to their restricted familiarity with such tasks. Practitioners and researchers may in these cases face uncertainty regarding whether underperformance stems from genuine skill deficits or from limited exposure to the language or testing conditions.

Despite the current curriculum being efficient for most students, there are recent indications of decreased text comprehension among Swedish adolescents and that Sweden's international status in this regard has sunk since the last evaluation of Program for International Student Assessment (PISA). While proficient reading acquisition is multifactorial and certainly relies on well-developed methods both for assessment and instruction, the continued development of efficient screening methods is vital to identify struggling children as early as possible.

2.4 Eye tracking in education

Eye tracking has been used to study learning processes, and interventions in the educational setting (Jarodzka et al., 2013; Mason et al., 2015a; Tatler et al., 2014; Wehrmeyer, 2014). Such research has provided valuable information for eye movement models models of cognitive processing in learning situations (Mason et al., 2015b; Nelson & Cottrell, 2007). Additionally, insights into how students visually engage with learning materials can inform the design of more effective instructional materials and practices. The field of educational science is a relatively young area of applied eye tracking, though there is a growing body of research on different topics within adult education (Jarodzka et al., 2013, 2021; Liu, 2014; Mason et al., 2015a; Mikhailenko et al., 2022). The concept of applied eye tracking to study phenomena in early education is an even newer development. Searching the scientific databases for eye movement studies of children's reading in educational settings currently returns very few publications (but see Vorstius et al., 2014). Additionally, potentially interesting findings from studies on young, learning readers are thus far rarely implemented, partly because eye tracking technology remains inaccessible. There are no widely used solutions in the Swedish educational system. While digital technology has been extensively implemented in Swedish elementary schools, other forms of advanced technology is not prevalent. Thus, practical experience of how eye tracking-based tools work in the educational environment is thus far scarce.

Nonetheless, earlier work demonstrating how eye movements can be used to study reading from a developmental, individual-differences perspective (Ashby et al., 2013; Joseph et al., 2013) makes its potential role in reading assessments interesting. Previous studies using machine learning approaches have shown that eye movement measures can be utilized to identify literacy skills and detect reading difficulties with high accuracy (Jothi Prabha & Bhargavi, 2020; Liu et al., 2017; Nilsson et al., 2016; Raatikainen et al., 2021; Rello & Ballesteros, 2015). Most tests of reading skill that are used today require an either written or verbal

response by the child and a subjective evaluation of response accuracy made by the assessor. Eye tracking holds potential promise as a method for objectively and accurately assessing reading proficiency in young children, bypassing the need for overt responses and instead relying on a fundamental aspect of the reading process. Further research into its application and refinement could provide a better understanding of its utility in educational assessments.

3 Methodological approach

3.1 Ecological validity

The extent to which scientists succeed in measuring what they have set out to measure is a dilemma facing most researchers of disciplines where real-world phenomena are recreated for investigation purposes.

Ecological validity concerns the question of how well an experiment reflects the complexities of everyday life. Conceptually, it intersects external validity and deals with the extent to which study conditions resemble natural settings and ultimately, whether the findings of a study can be assumed to be true outside of the context they were discovered in. Egon Brunswik, who first described the underpinnings of ecological validity, initially referred to it as representative design. He argued that it is a crucial facet to the generalizability of findings, because all psychological processing represents adjustments to stimuli in environments where they naturally occur. Thus, a given psychological phenomenon can only be validly assessed if study conditions are representative of that environment (Brunswik, 1955). Later, and perhaps more pragmatic, accounts oppose dichotomous approaches toward representative versus experimental designs (Bronfenbrenner, 1977.; Diehl et al., 2017). Ecological validity is not a binary factor but can be achieved to different degrees through methodological choices involving research design and data collection methods. Weak ecological validity does not decrease the value of an investigation but is oftentimes a trade-off for high internal validity which might be warranted for study purposes. The implications of findings are not only determined by their generalizability, but by their relation to the wider context of the research field. Most scholars would agree that experimental research is vital to understanding complex behavioral phenomena. Decisions about study design should be guided by the state of knowledge in the field and a good deal of conceptual and empirical reflection (Lewkowicz, 2001).

Any area of science that focuses on human beings and human behavior, essentially always involves confounding influences, since human behavior can be unpredictable. The more closely the research environment resembles an environment where the phenomenon naturally occurs, the greater is the exposure to uncertainties found in the real world. This means that when investigating in real-world settings, there is less control over outside influences and factors that could impact the results. Needless to say, it is often important to control as much potential undue influence as possible. On the other hand, high experimental control often entails conditions which poorly resemble reality.

"...much of contemporary developmental psychology is *the science of the strange behavior of children in strange situations with strange adults for the briefest possible of time*" (Bronfenbrenner, 1977)

However, it is also true that when human behaviors are examined within actual humans, as tends to be the case in most eye movement research, a degree of ecological validity and generalizability is achieved even if other contrived factors within the investigation. To better understand the cognitive underpinnings of reading and inform theories of reading development it has been of great interest to, to as great extent as possible, isolate and study certain aspects of the mental processing involved in children's reading. Previous research on eye movement has most often used controlled experimental setups aimed at reliably measuring specific responses while minimizing the influence of extraneous factors, rather than mirroring real-world scenarios. This often involves conducting investigations in laboratory settings where precision in measurements takes precedence over, for instance, participant mobility. Consequently, participants may be constrained by head and chin rests, and in some cases, bite bars are utilized to reduce data noise. Monocular recordings may be employed to further mitigate disturbances. Researchers frequently utilize gaze contingent paradigms and stimuli featuring target items within varied linguistic contexts to examine pertinent constructs by manipulating different components. These stimuli encompass diverse content, shapes, and presentation formats.

3.2 Methodological considerations

In eye movement research, various measures of gaze behaviors are analyzed depending on the issues of interest (Andersson et al., 2010; Rayner, 1998; Reichle, 2006; Tatler et al., 2014). When specific cognitive processes during reading are considered, the gold standard is to examine gaze behaviors relating to specific

parts of the text (e.g., word-based eye movements). This category of measures has been informative to the understanding of the psycholinguistic mechanisms underlying children's reading.

When it comes to global analysis of eye movements during reading and descriptions of group level tendencies, the average duration of all the fixations that readers make (mean fixation duration) and the length of the forward gaze movements (saccade amplitude) can be useful (Kaakinen, 2021). The directional angle of the saccades can be informative to estimate how often the reader makes backtracks in the text, to get an idea of the relative ease that they experience while reading (for a review, see Rayner, 1998).

In the present research, the selection of eye movement measures was guided by several factors in the pursuit of ecological validity. To enable the data collection in a natural environment (the schools), a portable eye tracker was to be used, which in this case involved a lower sampling rate than what is available in laboratory grade trackers. The aim was to utilize an unrestricted eye tracking setup devoid of head rests, chin rests, or bite bars or other elements that would limit the participant's freedom of movement. Due to the needs generated in the intersection of several methodological choices, employing word-based eye movement measures was consequently considered less feasible than global eye movement measures. Given the scarcity of studies examining group-level patterns in large samples within naturally variable contexts, the focus was on investigating general gaze behavior during children's reading. As such, attention was directed towards three fundamental and robust eye movement measures, with an eye toward potential future implementation.

Overall, new technology has made it easier to do research outside of the confines of laboratories and for scientists to track occurrences in real-time in authentic environments. Previous work has showed that it is possible to study different aspects of adults' eye movements in highly variable contexts (for a commentary, see Kaakinen, 2021). Children's gaze behaviors in natural situations, specifically with regards to reading, have not been evaluated to the same extent. There is limited knowledge about generalizability of experimental eye movement findings from young readers to a wider population and how overarching developmental changes in eye movements are affected by limited experimental control. Essentially, we know much more about how children's eyes move when they read texts that are meant to trigger responses related to a cognitive construct within

the confines of the research lab, than in situations resembling everyday life. Earlier work has compellingly shown that variations in eye movement measures correlate with developing reading, but more research is warranted to understand its potential in this context. By studying eye movements and their connection to development of proficient reading in the educational environment, we gain access to ecologically generated data that could be informative both regarding its potential for reading assessment, how children's gaze behavior during reading unfolds in situations with limited experimental control and indicate whether it is feasible to study aspects of children's eye movements in a variable environment.

To address the identified limitations in knowledge in this field, this thesis explores the link between the eye movements during reading and word reading ability in school-age children within a setting designed to mimic real-life conditions.

This investigation incorporates the following methodological choices and components, which were deliberately employed to achieve an as ecologically valid approach as possible:

- Implementation of an unrestricted eye tracking setup.
- Collection of data within the natural environment of participants' schools.
- Capture of eye movements during normal reading of age-adapted texts.
- Utilization of a portable, screen-based eye tracker.
- Administration of a word reading assessment comprising tests of multiple skills commonly incorporated in pedagogical or clinical assessments of word reading proficiency.
- Inclusion of a naturally diverse sample.

3.3 Research aims

Children's reading proficiency is reflected in their eye movements during reading, a subject predominantly explored in experimental settings. It is uncertain how these findings translate to ecological contexts. The primary aim of this thesis was to examine aspects of children's reading ability and eye movements in an ecological environment to study:

- The global, developmental features of children's eye movements during text reading and their relationship to skills that support reading development

- The extent to which eye movements during text reading reflect later word reading ability in children, in comparison to current word reading ability

- Potential indications of persistent word reading difficulties in eye movements during early literacy.

The overarching goal was to contribute to a more comprehensive understanding of the feasibility of studying children's eye movements in ecological settings and of assess the potential of eye movement analysis for reading assessments in the educational environment.

3.3.1 **Specific research questions**

- "… to investigate whether the global developmental trends of children's reading eye movements are present in data from an unrestrained and naturalistic eye tracking set-up in a large and inclusive sample." (Developmental changes – Study I)

- To what extent do eye movements recorded in first and second grade predict word reading ability at the time of recording and one year later?
- Does the amount of explained variance in word reading ability decrease in the longitudinal model compared to predictions made the same year and if so, by how much?
- Is the decrease larger in either sample? (Longitudinal robustness – Study II)

- Are children's eye movements during reading at baseline indicative of reading level in first, second and third grade?

- Are eye movements of children at baseline indicative of reading level one year later?

- Are children with below average word reading ability one year later identifiable based on their eye movements during text reading one year earlier?

- What are the characteristics of children with persistent difficulties in terms of eye movements at follow-up? (Early indications of reading difficulties – Study III)

4 Materials and methods

4.1 Overall project

A multipart word reading assessment and eye movement measures were collected from 2876 Swedish children in elementary school. The participants were between 7 and 9 years old and resided in two different municipalities: Järfälla and Trosa outside of Stockholm, Sweden.

*Figure 1. Summary of project design. *n = 93 in the second part of the analysis in Study III.*

4.2 Study design

The study design consisted of a word reading assessment involving six different tasks (visuomotor skill, phonological retrieval, phonological decoding and two measures of word recognition on the lexical level and text reading sentence/discourse). The participants' eye movements were recorded during the text passage reading and analyzed in terms of fixations, forward saccades and regressive saccades. The data was collected at the respective schools attended by the children, during their regular school day. Data collection was carried out during the spring semester of 2015 and 2016, i.e., twice, with one year in between. The eye movement data and most of the reading assessment was recorded in a separate room adjacent to the classroom (see figure 2). The visuomotor task and one of the word recognition tasks were carried out in class (Letter Chains and Word Chains, see below). The testing and recording session were kept brief to enable high participation rates and to ensure that the procedure was viable for implementation in educational settings.

Figure 2. An experiment leader and participant during data collection.

4.2.1 **Word reading assessment**

The assessment consisted of six tasks to test the participants' word reading ability. Visuomotor skill was tested by letting the participants identify identical letters within strings of mixed vowels and consonants. The participants were presented with the standardized test Letter Chains (part of Läskedjor-2; Jacobson, 2015) which contains 96 ten-letter-strings. Each chain of letters contained two pairs of identical letters and participants were asked to draw a line in the middle of each pair and to complete as many as possible within the time limit of two minutes.

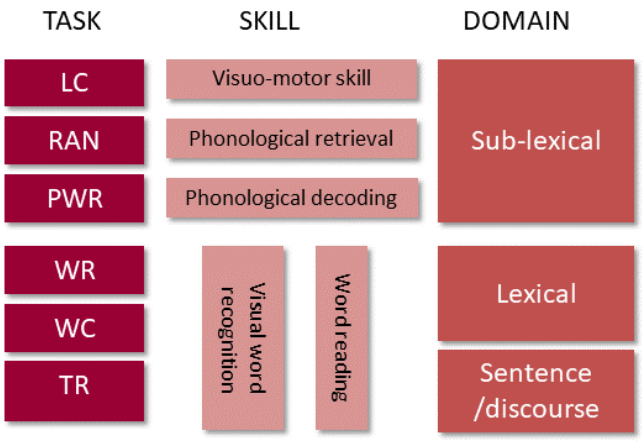

Figure 3. LC = Letter Chains. RAN = Rapid automatized naming. PWR = Pseudo word reading. WR = Word reading. WC = Word Chains. TR = Text passage reading.

An adapted version of Rapid Automatized Naming was used to test *phonological retrieval*. It was presented as a serial, alphabetical rapid naming task based on the version in the Comprehensive Test of Phonological Processing (CTOPP-II; Wagner et al., 2013). Outcomes on RAN tasks offer insights into various cognitive processes important to reading, notably phonological processing skill. The outcome is referred to as a proxy for phonological retrieval, assuming that several underlying skills and abilities may support this activity (Denckla & Cutting, 1999a; Powell & Atkinson, 2021; Stappen & Van Reybroeck, 2018b; Wolff et al., 2023) and that performance on RAN tasks provides information about several cognitive processes that influence reading (Wolff, 2014; Wolff et al., 2023). The participant was asked to name the 36 lower-case letters (s, a, n, c, k and t) as fast as they could. The letters were presented in four rows of nine items each. The primary metric derived from was the time taken by participants to name each item in the series.

Phonological decoding was tested using a pseudoword (phonological) oral decoding task. It consisted of 8x8 pseudo-words ordered by increasing complexity below. The participants were asked to read aloud as many pseudo-words as possible within the time-limit of 30 seconds. *Word reading* was tested in an identical manner, using real word stimuli. These words were utilized to construct the pseudo-words through a grapheme-replacement method based on place and manner of articulation. The test protocol was designed by Gustaf

Öqvist Seimyr in 2015 and is based on the principles of TOWRE (first edition; Wagner et al., 1999).

Visual word recognition was evaluated in Word Chains which constitutes the second part of Läskedjor-2 (the first part is Letter Chains, described above). The participants were asked to mark the boundaries between individual words, presented in series of strings (i.e. written consecutively, without blank spaces). The test contains 80 three-word-strings consisting of a mix of nouns, adjectives and verbs. The time limit was two minutes.

Text reading was through a text passage reading task. The task was to read a normal text paragraph either silently or aloud. The texts were fictional, age-adjusted and dealt with everyday topics. This task had two purposes – it was used to measure the subject's reading speed and was also the stimuli in the eye movement recording. A set of two texts was developed for each grade, with the assistance of a special educations' teacher.

The outcomes of the assessment described above served as dependent variables in this study, either in part or in its entirety.

4.3 Eye tracking

A Tobii T120 eye tracker was used to record the participants' binocular eye movements. The eye tracker uses infrared light to illuminate the eyes and specialized cameras capture the reflection patterns of the cornea and the eye's surface. The recording was initiated by a five-point calibration procedure. Eye movement data was recorded throughout the testing process, but the eye movements of interest in this work were recorded during the task measuring reading on the sentence level, i.e. during text reading. Thus, the eye movement measures in study I, II and III are taken from the text reading task.

Figure 4. Illustrative purposes only; not data from the present project. Obtained and used with permission by Gustaf Öqvist Seimyr. Fixations are visualized as circles, the larger the circle, the higher duration. Saccades are represented by lines between the circles, indicative of the subject's gaze movements.

The analysis of eye movement data was conducted using Optosphere (Version 2.1) as described by Nilsson et al. (2016). The software uses a classification system of events based on eye movement characteristics. Specifically, a fixation was identified when the eye remained within the fovea area for at least 50 ms. Saccades were categorized based on whether they occurred within or outside the perceptual span, and further distinguished as progressive (45–224 degrees) or regressive (224–45 degrees) based on their directional angle. Mean duration was examined for fixations, while saccades were analyzed based on directional angle, amplitude, and the proportion of regressive saccades. These are referred to as mean fixation duration, forward saccade amplitude and proportion of regression in the continuation of this thesis.

4.4 Ethical considerations

The research protocol for this work has received approval from the Central Ethical Review Board (Ö 13/2015). Two of the overseeing researchers (Mattias Nilsson and Gustaf Öqvist Seimyr) met with principals, teachers, and caregivers during parent-teacher meetings to provide information about the study, ahead of its start. Additional details and consent forms were sent to the homes of all caregivers. Participation was offered to all first, second, and third-grade students if they had obtained their caregivers' consent. Individual consent was obtained at the time of testing, with participants informed of their right to withdraw from the study at any point. Given children's vulnerability, particular care was taken to ensure that the language used in the individual consent process and during the recording session was age-appropriate and comprehensible. All participants were from schools following a standard curriculum. None were enrolled in the Compulsory school for pupils with intellectual disabilities.

4.5 Analysis

A set of mixed effects linear regression models were applied to the dependent measures in study I. School grade was set as a random variable. In study II, the relationships between eye movement measures and word reading ability were investigated in two sets of multiple linear regression models, where eye movement variables were entered as independent measures and the outcomes of the word reading assessment was combined in a composite variable. In Study III, the outcome data from the reading assessment was categorized into reading levels according to quartile distribution. A measure of dispersion was utilized in this instance because of its facilitation of normative and ipsative comparisons, as well as its alignment with practical assessment procedures.

Kruskal-Wallis tests were conducted in the case of three groups and Mann-Whitney U in the case of two groups. Wilcoxon signed-rank tests were used for post-hoc comparisons following Kruskal-Wallis tests and post-hoc analysis, and Benjamini-Hochberg correction were used to counteract false discovery rates.

In Study I, each test from the word reading assessment was analyzed as a separate outcome measure. In study II and III, the results of the word reading assessment were combined in a composite variable to generate a global measure of word reading ability. Letter Chains was excluded from the composite variable due to weak correlations to the majority of the other tasks. The outcomes of the assessment were standardized using z-transformation and simple averaging. The equal weighting approach was deemed suitable because it is straightforward and transparent, reducing researcher bias, even though it suggests some potential trade-offs regarding the composite's sensitivity.

Regarding the population, it was analyzed in its entirety in Study I and as appropriate, split into clusters according to grade. In Study II and III the sample was filtered for students who only had participated once, meaning the sample consisted only of students who had been recorded twice. It was split according to grades and according to the cycle of data collection, i.e., 2015 or 2016. One subsample had participated when attending first and second grade, while another subsample had participated in second and third grade. These groups are referred to as “sample A” and “sample B”, in Study II and “First to second grade” and “Second to third grade” respectively in Study III.

5 Results

5.1 Developmental features (study I)

We observed the highest correlations between mean fixation duration and outcomes within the lexical domain (Word Chains, word reading and words per minute). As fixations duration increased, lexical outcomes decreased. This tendency remained and increased in strength across grades. The strength of the association between forward saccade length and lexical outcomes increased across grades. The correlation between regression probability and essentially all tests decreased slightly in strength.

When controlling for grade, eye movement measures explained approximately half of the variance in test results with outcomes within the lexical domain. The test of word reading (word list) revealed that eye movement measures explained 56% of the variance, while grade accounted for an additional 12%. Grade explained 2.5–12 % of the variance in test scores when test contents were identical for each grade, it accounted for 26–33 % of the variance when the test contents were different in each grade or when the tests were taken in the classroom setting (i.e., separate according to grade).

5.2 Longitudinal robustness (study II)

5.2.1 Concurrent analysis of eye movement measures and reading ability

The regression equation was significant [$F(3, 160) = 80.64$, $p < 0.001$] in sample A. The independent variables (mean fixation duration, forward saccade amplitude and regression probability) explained 59 % of the variance in the dependent variable in first grade. Similarly, there was a significant regression equation in sample B [$F(3, 202) = 107$, $p < 0.001$], where the independent measures accounted for 61% of the variance in second grade (see figure 5). This means that eye movement measures explained approximately 60% of the variance in reading ability recorded the same year.

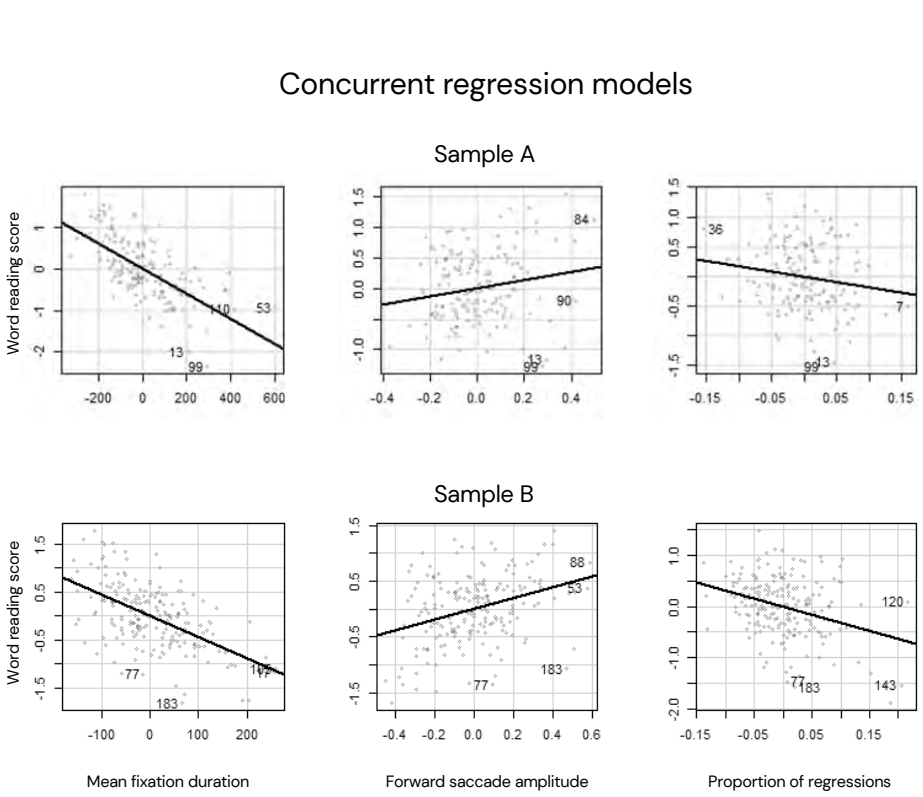

Figure 5. Independent coefficient plots of the relationship between the z-score for the word reading assessment and each of the eye movement variables separately, while controlling for the other independent measures (i.e., the other eye movement variables).

5.2.2 **Longitudinal analysis of eye movement measures and reading ability**

There was a significant regression equation in sample A [$F(3, 160) = 43.41$, $p < 0.001$] (see figure 6). The independent measures accounted for 44% of the variation in the dependent variable. This means, eye movements recorded in first grade explained 44% of the variance in reading ability in second grade. In sample B, the regression model was significant [$F(3, 202) = 63.23$, $p < 0.001$]. The independent variables accounted for 48% of the variance in the dependent measure meaning that eye movements recorded in second grade were associated with 48% of the variance in reading ability in third grade. On average, eye movement measures explained 46% of the variance in reading ability one year later.

The longitudinal model explained 15 percentage points less of the variance in word reading ability than the concurrent model in sample A. In sample B, the equivalent difference was 13 percentage points.

In each model, there were significant, inverse relationships between the average duration of fixations and the value of the composite variable (for every additional 100 ms of fixation, the composite score decreased by 0.3 z-scores). Similar relationships existed between regression probability and reading ability, however only reaching statistical significance in the analysis of the older sample (i.e. children in second/third grade). Increased saccade amplitude had a direct effect on the dependent variable (for every increase in amplitude, there was an 0.68 z-score increase in the composite variable).

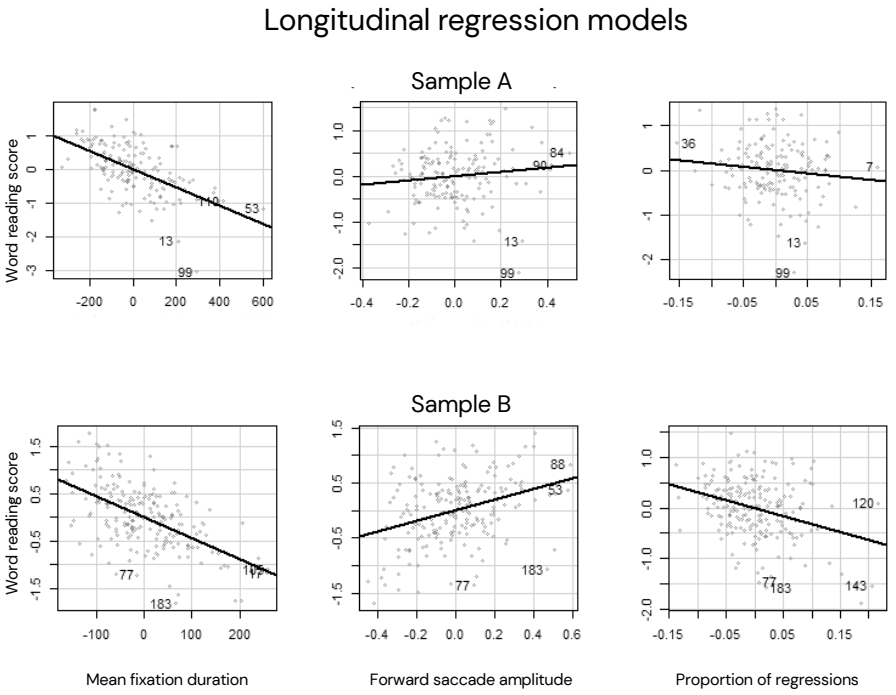

Figure 6. Independent coefficient plots of the relationship between the z-score for the word reading assessment and each of the eye movement variables separately, while controlling for the other independent measures (i.e., the other eye movement variables).

5.3 Early indications of reading difficulties (study III)

There were significant differences in eye movement measures among students within first, second and third grade, depending on their reading level. Post-hoc analysis revealed significant differences between all pairs of groups (below average, within average and above average) regarding mean fixation duration and forward saccade amplitude. For regression probability, the difference was significant only between the average and above-average group in first grade.

Further comparisons showed that differences remain in the relationship between eye movement measures at baseline contingent on reading level one year later. Subsequent examination of sample A and sample B showed that there were significant differences in mean fixation duration and forward saccade amplitude in all pairs of groups.

The group of children in sample A who had persistent difficulties (i.e., below average result on the reading assessment in first and second grade) had longer fixations, shorter forward saccades and were more likely to reread text at baseline, than the group of children whose reading ability had improved by second grade. However, the differences were not significant. In sample B, children with persistent difficulties had longer fixations, shorter saccades and higher regression probability at baseline than their peers whose reading outcomes had improved by third grade. The difference was significant with regards to mean fixation duration ($U = 142$, $p < .05$). An average of 480 milliseconds fixation duration indicating a below average result at the one-year follow-up in third grade.

At the follow-up assessment, both readers with below-average results and those with improved results had significantly shorter mean fixation duration and longer forward saccades than they had at baseline. The difference relative to baseline measurements was relatively greater among the children who improved. Mean fixation duration and forward saccade amplitude also differed significantly *between* those two groups at follow-up, meaning that the group who had scored below average twice had significantly longer fixation durations and shorter forward saccades. In sample B, regressions were slightly lower in children with persistent difficulties, however not significantly different. Improving readers also had somewhat higher probability of regression at follow-up than baseline.

6 Discussion

In this section, I discuss and contextualize each study's key findings in relation to the research questions outlined in the Introduction.

- Developmental eye movement findings during children's reading in relation to reading development in ecological circumstances in a population of school-aged children (study I)
- The potential of eye movement analysis in assessment of reading ability in a longitudinal perspective (study II).
- The role of eye movement analysis for identifying specific characteristics of persistent RD (study III)

6.1 Developmental changes (study I)

6.1.1 Summary of main results

- Mean fixation duration decreased significantly with each higher grade, while forward saccade amplitude increased. Regression probability, on the other hand, only decreased between first and second grade, and remained on the same level in third grade.
- Increased fixation duration and saccade amplitude compared to earlier work
- Across the grades, the highest correlations were found between mean fixation duration and outcomes of tests within the lexical domain. The strength of this association increased with higher grade. The link between forward saccade amplitude and results within the lexical domain was not as strong but increased with increasing grade. Regression probability showed no more than weak to moderate association to any test.
- Grade had the greatest effect when test contents was differentiated according to grade or taken in the classroom setting, but otherwise accounted for 2-12 % of the variance. Eye movements explained up to 56 % of the variance in the dependent variable (word reading).

6.1.1.1 Discussion of main results

Previous work has shown that there are changes in children's eye movements during reading which reflect their progress as readers. In this paper I investigate

this relationship in the educational environment. Developmental changes in gaze behavior during reading and the relationship between eye movement measures and word reading ability were analyzed. Overall, the variations in eye movement measures across grades corroborate the overarching developmental trends reported in earlier, primarily experimental contexts (Blythe, 2014; Blythe et al., 2006, 2009, 2011; Miller & O'Donnell, 2013; Reichle et al., 2013b). Findings reinforce a tight connection between variations in eye movements and variations in word reading ability (Blythe & Joseph, 2011; Blythe et al., 2011; Joseph et al., 2013; Rayner, 1986; Tiffin-Richards & Schroeder, 2015; Wertli et al., 2022). This paper shows that it is possible to reproduce this link in a context with limited experimental control.

The proportion of regressions decreased between first and second grade, and then remained approximately the same between second and third grade. The length of forward saccades increased. These changes corresponded with higher scores on the word reading assessment.

6.1.1.2 Contextual influence on eye movement measures

The dynamics of these changes imply a decrease in processing difficulty related to age and familiarity with printed language and show that variations in word reading skill during this part of reading development was reflected in the participants' gaze behavior. These findings align with the general assumption about the operating mechanisms of children's eye movements during reading (Blythe, 2014; Blythe et al., 2011; Joseph et al., 2013; Rayner, 1986). Processing difficulty during reading manifests through subtle variations in the duration of fixations on words and the length of gaze movements (Blythe, 2014; Rayner, 1977, 1978, 1986). Results suggest that this notion gains support in a variable, educational setting involving a diverse sample that includes groups sometimes overlooked in research, such as learners of a second language and children with neuropsychiatric conditions.

Although this study did not evaluate the underpinning cognitive processes among these children in an experimental manner, its findings suggest that lexical processing influences the associations between word reading outcomes and eye movement measures. This inference is based on the strong correlations between mean fixation duration and performance on grapho-morphemic level tests, which depend on lexical processing (Inhoff & Rayner, 1986; Rayner, 1977, 2009; Rayner & McConkie, 1976).

The average fixation lasted longer, the forward saccades were generally shorter, and the descriptive statistics revealed substantial variability in the eye movement data, compared to previous studies, which suggests the impact of ecological factors within the study's design. Specifically, the analysis of global eye movement measures across complete text passages, alongside considerations of the diverse participant sample (including children with very limited experience of printed language), likely contributed to this finding. Furthermore, eye movements during both oral and silent reading were included, potentially affecting fixation times, which are typically prolonged during oral reading. (Vorstius et al., 2014). Alternatively, these values reflect a decline in word reading proficiency and/or text comprehension (Skolverket, 2021), a development that previously has been highlighted in North American adolescents in an eye movement study by Spichtig et al., (2016). Analysis of gaze behaviors could provide interesting contributions to the understanding of contemporary reading skills in relation to reading habits and environmental factors in young Swedish populations. However, in this case, I submit that the increased variation reported here should be interpreted as caused by specific elements inherent to this study. Increased variability in ecologically generated data is an expected finding (Kihlstrom, 2021) while no developmental eye movement research has focused on the effects of contemporary reading habits in Swedish children so far. Reduced experimental control in this research limits the possibility of unraveling variations in the eye movement data further.

While the findings regarding fixation duration and forward saccade amplitude are logically compelling and the developmental trajectories seem to correspond to previous findings (Blythe et al., 2009; Inhoff et al., 1991; Joseph et al., 2013; Rau et al., 2015; Rayner, 1998, 1986; Tiffin-Richards & Schroeder, 2015), there was essentially no difference in the proportion of regressions between second and third grade. Hypothetically, this could be reflective of the fact that there simply is no difference in the proportion of leftward gaze movements of second compared to third year students. Earlier reports have found the decline in regression rates less steady across age-groups in beginning readers than, for instance, the decrease in fixation duration (McConkie et al., 1991; Rayner, 1986). However, a global measure such as regression proportion may fail to identify important information. With improved reading proficiency, children make fewer and fewer regressive refixations within the currently fixated word and more frequent regressions to words earlier in the text. Intra- and inter-word regressions reflect

distinct cognitive processes within adult reading, wherein numerous regressions occur primarily to facilitate comprehension at a higher level (Inhoff et al., 2005). While the proportion of backward saccades may remain constant during second and third grade, a shift to more frequent inter-word regressions across age groups suggest a shift from predominantly decoding- towards comprehension-related efforts, which are not reflected in the proportion of regressions (Inhoff et al., 2019).

Fixation duration contributes significantly to explained variance in word recognition. Mean fixation duration increased with low test scores on tests in the lexical domain, which points to the link between lexical processing and fixation duration (Blythe et al., 2009; Inhoff, 1984b; McConkie & Rayner, 1975). Grade explained less variance than the eye movement measures, except regarding the tests with differentiated contents per grade or those that were conducted in the classroom setting (e.g. separately per grade). This attempt at reliably unraveling the actual effect of eye movement measures and account for unobserved heterogeneity could be further improved by a close-grained control of conditions and participants (Roback & Legler, 2021.) although, at the potential cost of decreased ecological validity.

6.2 Longitudinal robustness (study II)

6.2.1 Summary of main results

- Eye movement measures explained ~60% of the variance in word reading ability measured the same year in in 7- and 8-year-olds
- One year later, eye movement variables explained ~46%
- The amount of explained variance decreased more between grades in the younger readers

6.2.2 Discussion of main results

The purpose of this study was to investigate the predictive capacity of children's eye movement measures on subsequent word reading proficiency. As in the previous study, the goal was to investigate this association within a naturally varied participant pool, striving for ecological validity. To achieve this, I assessed if eye movement measures accounted for the variability in word reading skill, both in the present and one year later in two samples of children.

The pattern that emerged in the eye movement data maps onto current models of how children learn to read words. During the early phase of reading

development, children primarily focus their attention and effort on decoding small linguistic units. As their reading skills progress, there is a gradual transition towards recognizing larger units of text. This evolution corresponds to a shift from predominantly sub-lexical processing to lexical processing and higher-order comprehension operations (Ehri, 2005, 2014b; Inhoff, 1984, 1990; Inhoff & Rayner, 1986). In the present study younger readers, who tend to depend on sub-lexical processing to a high extent, had a higher number of short forward saccades, longer fixation durations and more frequent regressions than the children who were one year older. Hypothetically, this reflects the sub-lexical, decoding-related efforts that are prevalent in the early phases of reading development (Blythe, 2014; Blythe et al., 2011; Reichle et al., 2013a). In both first and second grade students, a higher word reading score correlated with shorter fixation durations, longer forward saccades, and fewer instances of regressions. These findings suggest that improved reading ability is manifested through developmentally contingent changes in eye movements within these groups.

6.2.2.1 Eye movements as predictors of word reading ability

Results showed that the model of three eye movement measures accounted for approximately 60% of the variance in current word reading skill and that the predictive validity of the model decreased with approximately 14 percentage points until next year. Mean fixation duration emerged as the most significant predictor of word reading skill in both samples. Saccade length and proportion of regressions also contributed to the predictive models, albeit to a lesser degree.

The lesser influence of forward saccade length in the model may align with developmental word reading models and previous eye movement research. Despite correlating with word reading score, forward saccade amplitude is likely a less important predictor because some participants partly rely on sub-lexical processing and small-unit decoding, which young readers of transparent orthographies tend to do (Cain et al., 2004; Ehri, 2005, 2014a; Joseph et al., 2013; Rau et al., 2014). Thus, saccade length may not be a strong correlate to subsequent word reading ability in children this young, where a majority is in early phases of reading development and rely on small-unit, letter, or syllable-focused decoding.

Regarding the limitations of global eye movement measures, which I discussed in the previous analysis of Study I, the overall proportion of regressions fell within expected ranges but did not significantly predict longitudinal word reading ability among the youngest participants. The properties of this measurement make it

inadequate to capture the dynamics of word reading skill and leftward gaze movements. Alternatively, measures of regressive eye movements do not provide meaningful insights into subsequent word reading proficiency during initial stages of reading development, when children often read each word slowly and sequentially. While the first explanation does not exclude the latter, it is likely that some variability in word reading skill is linked to the tendency to make eye movements opposite the reading direction, though perhaps to more fine-grained measures of them that reflect differentiated mental operations. If so, utilizing word-based measures and linguistically varied target stimuli elucidate patterns beyond what has been done within this investigation.

Phonemic awareness and RAN are known independent predictors of different aspects of early phases of reading (Denckla & Cutting, 1999b; Wolff, 2014). The present findings point to the potential of eye movements for predictive analysis of word reading ability, with the added value that eye movements can be analyzed during silent reading without subjective scoring (Kim et al., 2019). The fact that the explained variance decreases somewhat in the longitudinal models seems logically coherent. Construct validity assessments of word recognition tests report correlation coefficients ranging from .72 and .78 regarding criterion tests of oral and silent reading measures (Word Chains, 1st ed.; Jacobsson, 1998) and .89 to .96 word-level and reading fluency measures (Tarar et al., 2015). Though not a comprehensive validity assessment, this study serves as an initial effort to gauge the validity of eye movement measures during normal reading of age-adequate text passages, captured in authentic settings, as potential predictors of subsequent word reading proficiency. From that standpoint, the relationship reflected by this rather straightforward model, using ecologically generated data, appears clear and reasonably robust over time. It offers support for the application of eye movement analysis, in this environment. Nevertheless, the results prompt exploration of methods for improving the predictive capacity of this model, while maintaining a naturally variable study environment. For instance, it could be useful to separate oral from silent reading, include additional data points and implement growth modeling techniques as these strategies could enhance the validity of predictions and allow for a more comprehensive analysis of reading development over time.

6.3 Early indications of persistent reading difficulties (study III)

6.3.1 Summary of main results

- Significant differences in eye movement measures between reading levels in 1-3rd grade
- Significant differences in 1st and 2nd grade in mean fixation duration and forward saccade amplitude at baseline depending on subsequent reading level
- Significant difference in baseline (2nd grade) mean fixation duration among struggling readers depending on reading level (below average or within average) at follow-up (3rd grade)

6.3.2 Discussion of main results

This study aimed to investigate possible differences in eye movement measures as early indications of word reading difficulties in school-age children. The ultimate objective was to differentiate between children experiencing persistent challenges in reading and those showing improved word reading skill between the first and second assessment (e.g., individuals scoring below average due to factors other than genuine skill deficits). To investigate these issues, I analyzed the association between eye movement measures and word reading proficiency levels among school-age children at two distinct time points.

There were general differences in eye movement measures in each grade as a function of reading level, with a few exceptions. There were differences in first and second grade depending on the subsequent reading level emphasized their informativity. Mean fixation duration and forward saccade length stood out as the most important variables. Readers with scores within average in third grade had significantly smaller proportion of regressive saccades in already in second grade, than those who scored below average in third grade. This means they re-read less often, and that that is a meaningful difference in terms of subsequent word reading skill.

The most interesting finding concerns the group of children in second grade who scored below average. There was a significant difference in mean fixation duration at baseline, i.e., when they were approximately eight years old, depending on if their score remained in the lowest quartile or if it improved in the follow-up testing.

This finding suggests that it is possible to differentiate between children with persistent word reading difficulties and children who may not suffer from a true skill deficit, based on their early eye movements during text reading. Early identification of reading difficulties is feasible as early as second grade, offering promise for assessment purposes, given the importance of early intervention in addressing reading difficulties. In reading assessments, floor effects pose challenges, particularly among very young children, necessitating methods to distinguish between readers with genuine skill deficits and those with low scores due to limited exposure to print. Regardless of the underlying causes of difficulties, children with difficulties or delays in reading development require support. However, variations in underpinning causes may justify tailored interventions.

There were slightly larger differences between baseline and follow-up in the subsample of 7- to 8-year-olds ("First to second grade"). Speculatively, this reflects a significant developmental transition between first and second grade, during which the children's attention gradually shifts from grapho-phonemic to grapho-morphemic level operations (Ehri, 2005). Turning to the smaller subgroup of readers with scores in the below average reading level, there were no significant differences with regards to eye movements as a function of subsequent reading level, meaning it was not feasible to make the same differentiation between readers as in the slightly older sample (i.e. "Second to third grade", as discussed above). This emphasizes two sides of one and the same issue: the complexity and challenge of studying the relationship between eye movements and developing reading in its earliest phases, and that there might be other, potentially more informative, approaches to elucidate what variations and at what point eye movement measures can be indicative of later reading ability.

In the absence of an exact measure of proficient reading or a universally agreed-upon definition of what constitutes reading difficulties, the five tests included in this assessment are assumed to provide a fairly valid depiction of reading ability (correlation coefficients are reported in study I; RAN and Word Chains validated externally in Denckla & Cutting, 1999b, Denckla & Rudel, 1972 and Jacobson, 1998). The purpose of this study was to investigate the link between eye movement variables and subsequent ability in children who scored below average on a word reading assignment. This intent required a set cut-off, defining the boundaries of below versus within average performance and some sort of operationalization of persistency. Due to the sample being significantly smaller in this part of the investigation, compared to earlier analyses as well as study I and II, quartiles were

considered feasible for meaningful analysis (Badian, 1994)., with respect to the objectives of the study. A score within the first quartile at both baseline and follow-up, i.e., two years in a row, was categorized as a persistently low performance. I submit that this is a reasonable operationalization, albeit granular, which limits the potential clinical implications of these findings. This process involved uncertainty regarding the observations with proximity to the cut-offs and, as tends to be the case when grouping data, a degree of information loss. Hypothetical changes in word reading score at follow-up, which fell within the boundaries of the baseline quartile, may represent substantial changes that go unnoticed in this model.

While it may seem counterintuitive to label and categorize a complex ability like reading, it is more a byproduct of contextualization. The idea was to contrast groups using a method commonly employed in clinical and educational assessments of reading, where the interpretation of test outcomes is guided by their relative position within the normal distribution. In psychometric testing, a common criterion for delineating levels of reading proficiency starts at 1.5 standard deviations below the mean for below-average performance on a normal distribution. Alternative metrics, such as percentiles or Stanine scores, also offer a more fine-grained analysis when applicable.

The results of this study should be interpreted with caution for several reasons. In part, because the relationship between eye movements and reading proficiency can be volatile in early reading development (Kim et al., 2019). Additionally, the sample is reduced (addressing research question 3-4), which, together with limitations in experimental control, needs to be considered in terms of the validity of the findings. Future work could consider the possibility of identifying latent classes of subgroups of struggling young readers based on their eye movements and explore the relationship to word reading skills and comprehension.

6.4 Methodological discussion

To achieve the objective of investigating children's eye movements and word reading ability in authentic settings, specific methodological strategies were adopted, including: conducting data collection within participants' school environments, employing an unrestricted eye tracking setup, capturing eye movements during normal age-appropriate text reading, utilizing a portable screen-based eye tracker, administering a word reading assessment covering various skills commonly assessed in educational or clinical contexts, and ensuring

inclusion of a naturally diverse participant sample. With regards to eye movement measures, three basic eye movement measures suitable for global, group-level analysis were selected.

While prior research has indicated the potential of eye movement findings to inform practice (Miller & O'Donnell, 2013), there is limited knowledge regarding children's eye movements and word reading skills in authentic contexts. The practical applications of eye tracking for assessment purposes remain largely unexplored, and there is a lack of documented experience in implementing eye-tracking-based tools in relevant settings, such as educational environments.

The present study aimed to address this limitation by collecting data within naturalistic school settings. Although this introduced risks of undue effects of disturbances in the physical environment, it allowed for the observation of eye movements in environments reflective of real-world reading experiences. An unrestricted eye tracking setup further allowed participants to engage in natural reading behaviors without constraints.

While using a portable eye tracker was critical to the be able to record and examine ecologically generated data, as it enabled data collection within the participants' actual educational environment, it involves limitations when compared to stationary, laboratory-grade eye tracking systems in terms of accuracy and precision. These limitations may have implications for the validity of the collected eye movement data. Additionally, there were constraints to the measures that could be feasibly investigated. Focusing solely on global eye movement measures of text reading might overlook subtle variations in reading ability that could have been elucidated by utilizing more sensitive measures and advanced paradigms. Considering alternative approaches could offer different insights into reading proficiency in these age groups.

Adapting text passages to suit participants' age in terms of length and content was crucial to elicit naturalistic gaze behaviors relevant to their developmental stage, minimizing floor and ceiling effects in eye movement data. However, this approach complicates cross-grade comparisons. Utilizing randomized conditions of control text and adapted versions could address this issue, albeit potentially lengthening the testing procedure. The word reading assessment relied on several tests addressing word reading and skills that support word reading ability in the sub-lexical, lexical and sentence domain. Instead of relying on one or a couple of tests as representative of a quite advanced skill, this approach increases the

conceptual validity of the word reading assessment composite measure that was generated for study II and III.

The word reading assessment encompassed multiple tests targeting various aspects of word reading and skills that support word reading, across the sub-lexical, lexical, and sentence domains. By incorporating several, diverse tests rather than relying on just one or a few, this approach enhances the conceptual validity of the word reading assessment in study I and the subsequent composite measure of word reading that was generated for studies II and III.

Finally, the inclusion of a diverse participant sample enhances the generalizability of the findings and acknowledges the variability in reading development across different populations. However, this approach comes with the trade-off of limiting the ability to account for factors such as language background and socioeconomic status that may influence the results. Readers should therefore remain mindful of these limitations and consider their potential impact on the interpretation of the findings.

One final observation that could enable conclusions about the impact of specific factors in the research design, is to study the issues of interest and experimentally vary the presence of certain elements, such as using different types of eye trackers in different conditions or collect data in environments involving different degrees of control. This approach facilitates more definitive conclusions not only about ecological research designs in general but also about the influence of specific elements within different environmental contexts.

The studies reported in this thesis offer both indications that progressing word reading ability and developmental eye movements are feasibly investigated with high ecological validity and some insights into the effects associated with limited experimental control. In conclusion, the strategy outlined here was motivated by the overarching objective of this thesis. There are several considerations for methodological refinement to enhance the implications, which should be considered in future research in this area.

7 Conclusions

Overall, these studies add to the knowledge about developmental eye movements and reading development by corroborating findings from primarily experimental contexts, showing that the connection between variations in children's eye movements during reading development and progressing word reading skill is

reproducible in an authentic environment with normal text reading, using global eye movement measures and inclusive sample.

Coherent, developmentally driven changes in the eye movements during reading linked to word reading skill emerged in the data. The changes within this population of young readers corroborate earlier, experimental findings in an ecological environment. That suggests that it is feasible to study the relationship between eye movements and developing reading in environments with high resemblance to real-world settings. Additionally, this work showed that some measures (fixation duration and forward saccades) have stronger links to word reading skill than others (regressions) in this setting, specifically between second and third grade, highlighting the need for varied eye movements measures among closely aged groups at different points in time.

Furthermore, this research shows that eye movements account for variance in children's word reading ability in the present, with limited loss of predictive validity longitudinally. This emphasizes that there is a robustness and validity of eye movement measures in terms of predicting subsequent word reading skill. This could be informative with regards to potential implementations of eye movement-based tools in reading assessments, as it underscores the extent to which eye movements during reading are reflective of word reading ability, both in the present and one year later.

Finally, variations in mean fixation duration emerged as an early indicator of persistent reading difficulties and is distinguishing characteristic in readers with true skill deficits compared to children whose word reading outcomes have improved by the follow-up a year later. This suggests that there is potential utility of eye movement analysis in reading assessments, feasible as early as second grade, assisting timely identification and intervention. However, because the sample was quite limited in this analysis, these findings should be interpreted with caution, warranting further investigation and suggest ample room for refining and enhancing methods aimed at reading assessment based on eye movement analysis.

7.1 The potential of eye movement analysis of word reading in ecological and educational settings

In this section I make concluding remarks about the overarching goals of this thesis, to contribute to a more comprehensive understanding of the feasibility of studying children's eye movements in ecological settings and to assess the

potential of eye movement analysis for reading assessments in the educational environment.

By verifying links between gaze behavior and progressing word reading skill with minimal experimental control, the findings of this thesis support the feasibility of studying this relationship in variable environments. This conclusion suggests that reading development can be investigated using eye tracking technology outside of controlled laboratory settings, alleviating potential stress for children involved in the research process and facilitating natural reading behaviors.

The findings reported here advise researchers to anticipate relatively consistent associations between eye movements and reading measures even within naturalistic settings. Despite the absence of stringent control measures typical of laboratory environments, the established connections between these variables highlight the reliability of eye movement measures as indicators of ongoing, cognitive text processing. While the observed developmental patterns in eye movements and their correlation with word reading skills may seem intuitive, it was important to empirically investigate and validate these associations for potential practical applications.

Speculatively, the implications drawn from the findings of studies II and III suggest that integrating eye-tracking technology into evaluations of reading could support' assessments of reading development by introducing an additional predictive dimension. This integration could provide information based on the child silently or orally reading a short text passage, excluding the need for manual scoring. Another possibility is to use eye movement patterns to identify specific issues in the reading process. The results of this research indicate that while global eye movement measures offer a good deal of information about word reading skill, both in the present and one year later, investigating word-based measures may yield more nuanced details regarding specific reading difficulties.

Relating to the overarching theme of this thesis, the findings support the potential of eye-tracking tools for reading assessments in educational settings. The aim could be to complement existing assessment techniques. Eye movement analysis can serve as a supplementary assessment tool, offering rapid and objective evaluation without requiring overt responses which can be useful with students who find the assessment process taxing or where the assessor would like to add the dimension of an online measure to the evaluation.

The methodological choices in this study, discussed in detail above, were designed with consideration for the educational environment and the practical potential implementation of eye-tracking tools in schools. The results showed that eye movement measures from brief recording sessions explain variance in word reading ability across different ages through straightforward statistical analyses. A simplistic procedure was crucial to maintain applicability for educational settings, which presented both strengths and limitations to this research. The analyses in this thesis limits the possibility to draw definitive conclusions about underlying cognitive factors at play during reading. Unlike much of the fundamental research in this field, the approach was guided by reasonable psycholinguistic assumptions regarding the mechanisms of eye movements during reading. We sought indications that these mechanisms could be inferred from ecologically generated data and applied to the assessment of word reading skill. Other areas potential areas of interest for future research could involve examining differentiating skills within natural reader groups or investigating academic development beyond third grade within this sample.

In conclusion, while the findings of these studies point to several areas of improvement regarding investigations of eye movements and reading developments in authentic contexts, they also show that it is feasible to do so with minimal experimental control and thus support the potential of eye tracking technology in the educational environment with suitable adjustments and implementation.

8 Personal reflections and future directions

Throughout my doctoral project, I maintained an open and pragmatic stance towards analyzing and interpreting data from a context that is somewhat unconventional.

Beginning this journey - fresh, with the unbridled enthusiasm from completing my master's degree - I felt a compelling urge to explore issues raised in clinical settings regarding the validity of eye movement analysis, both in terms of reflecting skills during reading development and its applicability beyond laboratory settings.

Because the knowledge and experience of studying children's eye movements and reading in ecological settings was limited, an open mindset seemed suitable. I believe this approach has helped me in being open to the perspectives of

researchers in other, or adjacent, disciplines, from which I have learned immensely. Reading allows us to access worlds beyond our own. In the realm of science, reading is accessed by various research disciplines, each offering insightful perspectives.

A valuable insight that I have gleaned from these studies and reading the relevant literature pertains to the significance of behavioral measures. Modern technological progress have revolutionized our ability to measure and investigate cognitive aspects of reading and opened up new avenues for exploring previously unexplored terrain. However, the potential appeal of the speed and objectivity offered by such measures, may overlook the importance of offline, skill performance testing including the subjective assessment of the assessor. It is important, however, to recognize that our understanding of the skills and abilities assessed in traditional testing, and how they interplay in proficient reading and reading difficulties, informs the interpretation of behavioral measures like eye movements. This understanding ultimately facilitates the transition towards practical applications.

In the initial stages of this project, a senior colleague shared a valuable insight with me: that by the project's end, one often discovers that the most significant learning differs from the initial expectations. While I have undoubtedly deepened my domain specific knowledge of eye tracking and eye movement analysis, I find that my learnings are primarily focused on methodological aspects. Through the reflections I have done during my work and writing of this thesis, it has become clear how optimizing factors within a particular research design more than likely will compromise other factors, essential in different contexts, which was a palpable lesson. Nevertheless, this aspect has prompted me to reflect on the potential gains from explorative, contextually embedded research such as this doctoral project. Specifically for this research, its primary limitation of is also an asset. The exploratory nature, which focuses on achieving high ecological validity, restricts the conclusions that can be drawn from the results. However, these factors are also what makes it interesting. I have concluded that from the perspective of implementation, the results offer valuable insights as these as the findings are likely to reflect the true nature of these relationships within real-world educational environments. Ultimately, this is important for translational applications.

While the studies conducted within this project has led to several meaningful insights, there is always room for improvement. When considering future research directions in this subject area, it would be interesting to continue study the dynamics of this relationship in a naturally variable environment, while applying a slightly different approach that would allow control of certain factors. That way, the influence of environment on children's eye movements and reading ability could be experimentally investigated or at least reviewed alongside other methodologies.

One final important lesson relevant to my doctoral studies, and probably to life in general, has been to remain humble and persistent. Throughout a doctoral project, you frequently encounter challenges related to your current work or the direction you wish to take. Sometimes, it's necessary to step back and reconsider a decision. If I could offer one piece of advice to my previous self, it would be to embrace change, as it is essential for growth and helps you continue moving in the direction you believe in. To any researcher, it is a source of frustration to ponder the reasons behind certain findings and come up short on answers. However, dealing with these unanswered questions are a necessity, both in terms of working towards an understanding but also because they are what propel us forward.

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